GEOLOGY OF THE UPHEAVAL DOME IMPACT STRUCTURE, SOUTHEAST UTAH

Bryan J. Kriens

Department of Earth Sciences

California State University, Dominguez Hills

Carson, California 90747

Eugene M. Shoemaker[1]

U.S. Geological Survey and Lowell Observatory

Flagstaff, Arizona 86001

Ken E. Herkenhoff[2]

Jet Propulsion Laboratory, MS 183-501

California Institute of Technology

4800 Oak Grove Drive

Pasadena, California 91109

Submitted to the *Journal of Geophysical Research--Planets*

April 16, 1998

---

[1] Deceased July 18, 1997

[2] To whom correspondence should be addressed.

ABSTRACT

Two vastly different phenomena, impact and salt diapirism, have been proposed for the origin of Upheaval Dome, a spectacular scenic feature in southeast Utah. Detailed geologic mapping, seismic refraction data, and the presence of shock metamorphosed rocks indicate that the dome originated by collapse of a transient cavity formed by impact. Evidence is: 1) the occurrence of a rare lag deposit of impactites, 2) fan-tailed fracture surfaces (shatter surfaces) and rare shatter cones are present near the center of the structure, 3) the top of the underlying salt horizon is at least 500 meters below the surface at the center of the dome and there are no exposures of salt or associated rocks of the Paradox Formation in the dome to support the possibility that a salt diapir has ascended through it, 4) sedimentary strata in the center of the structure are pervasively imbricated by top-toward-the-center thrust faulting and are complexly folded as well, 5) top-toward-the-center normal faults are found at the perimeter of the structure, and 6) clastic dikes are widespread.

We show that the dome formed mainly by centerward motion of rock units along listric faults. Outcrop-scale folding and upturning of beds, especially common in the center, are largely a consequence of this motion. We have also detected some centerward motion of fault-bounded wedges resulting from displacements on subhorizontal faults that conjoin and die out within horizontal bedding near the perimeter of the structure. The observed deformation corresponds to the central uplift and the encircling ring structural depression seen in complex impact craters.

INTRODUCTION

Impact of solid bodies is the most fundamental geologic process in the solar system, having formed the terrestrial planets and satellites and modified their surfaces until the present. The surface morphology of craters has been studied extensively in recent years on other planets and satellites including the Moon, but only a relative handful of impact craters on Earth have been closely scrutinized. This is largely due to the fact that many of the craters on Earth are buried or obscured by vegetation and/or erosion. Upheaval Dome, located in Canyonlands National Park, southeast Utah, is the best-exposed complex crater in the world and thus one of the best places to study impact mechanics. Much of the three dimensional structure of Upheaval Dome is revealed in the deep canyons that have been cut into it.

Existing field studies of impact structures on Earth and the morphology of craters on the other terrestrial planets and on the Moon has led to the recognition of a variety of structural classes of craters. Small impact craters typically have a simple bowl-shape, and the rocks of their walls preserve much of the structure developed during passage of the shockwave and opening of an initial or transient cavity (Shoemaker, 1960). Above a certain threshold size, the transient cavity collapses, and a complex crater is formed. Rocks of the walls and rim of the transient cavity subside and are transported inward, generally along listric faults. The convergent flow forces the rocks underlying the transient cavity floor to rise in a structurally complex central uplift. On Earth, the transition from simple to complex craters occurs at crater diameters of about 2 kilometers in sedimentary rocks and about 4 kilometers in strong crystalline rocks (Grieve, 1991). Upheaval Dome is an example of a complex crater somewhat above the transition size. The dome and surrounding ring structural depression provide a particularly clear example of the deformation that accompanies transient cavity collapse.

HISTORY OF INVESTIGATION

Upheaval Dome was first noted during a reconnaissance geologic study by B.H. Parker, who hypothesized that the structure was due to salt doming (Harrison, 1927). Since then, the interpretation of this structure has been the subject of dozens of publications, and its origin continues to be debated. Bucher (1936) firmly advocated a cryptovolcanic origin for Upheaval Dome. Shortly thereafter, Boon and Albritton (1938) suggested that many of the Earth's cryptovolcanic structures were actually of impact origin, although they did not specifically mention Upheaval Dome. The first detailed description of Upheaval Dome was by McKnight (1940), who mapped the structure at 1:62,500 scale. While he considered that the structure might be of impact origin, he favored the hypothesis that the central uplift and surrounding structural depression were the result of salt flow in the underlying Paradox Formation. Shoemaker (1954, 1956) recognized clastic dikes of White Rim sandstone at the center of the structure and initially supported the cryptovolcanic interpretation, based also on the results of a geophysical survey that showed a pronounced magnetic anomaly over Upheaval Dome (Joesting and Plouff, 1958). At that time, little was known about impact structures, but it later became evident that Boon and Albritton were correct. As more impact structures were recognized throughout the world, it became possible to estimate the rate of impacts during the Phanerozoic within a factor of about 2 (Shoemaker, 1983). This cratering rate and the total area and average age of rocks exposed on the Colorado Plateau implied that a crater about 10 kilometers in diameter should be present on the Plateau. This calculation prompted further field work at Upheaval Dome, and an impact origin was suggested on the basis of the faulting and centerward motion of rocks that was observed (Shoemaker and Herkenhoff, 1984). Recently, however, Jackson *et al.* (1998) have interpreted these faults to record motion of rocks into a cavity left behind by the upward passage of a salt diapir, now eroded away.

GEOLOGIC SETTING

Upheaval Dome is located in the canyon lands region of the Colorado Plateau in southeast Utah (Fig. 1). Most of the region is underlain by nearly flat-lying to gently deformed sedimentary strata of Pennsylvanian to Cretaceous age (Fig. 2). Northwest-trending salt anticlines occur within the Paradox depositional basin of Pennsylvanian and Permian age (*e.g.*, Cater, 1970; Doelling et al., 1988). Small salt diapirs (300-400 meters across) and normal faults are found in The Grabens area at the south end of Canyonlands National Park (Huntoon *et al.*, 1982). Upheaval Dome, a 2.5 kilometer-diameter complex structural uplift surrounded by a 5 kilometer-diameter annular structural depression lies near the north end of the park (Figs. 3 and 4). The dome is located near the western margin of the Paradox Basin. The presence of known salt structures in the region influenced early interpretations that Upheaval Dome resulted from salt diapirism, but it is noteworthy that there are no other similar-size domal structures visible elsewhere in the Colorado Plateau and especially in the nearby area (Fig. 2). This is at odds with what is seen in known areas of dome formation by salt diapirism, which typically contain many such domes in rather close proximity to each other (*e.g.*, Worrall and Snelson, 1989; Jackson *et al.*, 1990). In addition to the above structures, the region contains a pervasive northwest- to north-striking subvertical conjugate joint system. Also present is a unique northeast-striking, circa 10 kilometer-long fracture (the Roberts rift) located approximately 25-30 kilometers northeast of Upheaval Dome and hypothesized to be the result of impact at the dome (Huntoon and Shoemaker, 1995).

Rock units exposed in the dome range from the uppermost formation of the Cutler Group (the White Rim Sandstone) of Permian age to the middle of the Navajo Sandstone of Jurassic age (Figs. 4 and 5). Strata shown in Figure 5 older than the White Rim Sandstone have been penetrated by drilling. On the basis of subsurface strata encountered in a drill hole in the eastern part of the ring structural depression, the top of the highest salt lies more than 500 meters below the lowest exposed surface outcrops (D. L. Baars, written communication, 1984; hole location shown on Fig. 3). A recent seismic refraction experiment confirmed that no salt is present within 500 meters of the surface in the central area of the dome (Louie *et al.*, 1995). No trace of salt or associated rocks of the Paradox Formation has been found among the complexly faulted rocks in the center of the dome to support the suggestion that a salt diapir has ascended through the dome.

STRUCTURAL GEOLOGY OF UPHEAVAL DOME

With the exception of the talus slopes below the Wingate Sandstone, the quality of exposure at Upheaval Dome is very high, roughly 75-90% bedrock. Along canyon walls, the exposure of structural features is remarkably complete. Faults, folds, and clastic dikes are conspicuous, and were mapped at a scale of 1:6,000 (Plate 1).

In general, the structure of Upheaval Dome is marked by a complexly faulted and folded central uplift in which the Moenkopi Formation and White Rim Sandstone have been raised approximately 350 meters in elevation compared to outcrops in the undeformed perimeter of the dome. The White Rim Sandstone occurs as beds and clastic dikes. Proceeding outward from the central uplift to the vicinity of a major syncline that encircles the uplift (the ring structural depression), there are circular outcrop bands of Chinle, Wingate, Kayenta, and Navajo units. In these outcrops, the Chinle and Kayenta formations are primarily folded and thrust faulted, whereas the massive Wingate and Navajo sandstones are mainly folded. Clastic dikes derived from Navajo to Wingate units are found in these outcrops, and some of the Wingate Sandstone appears to have flowed as tongue-shaped masses into or overlapping the Chinle Formation. All rock units for the most part dip away from the central uplift until the axis of the syncline is reached.

Outward from the syncline axis, rock units of the Navajo Sandstone to the Moenkopi Formation are exposed and dip toward the central uplift. In this vicinity there are faults that omit stratigraphic section. A few clastic dikes presumably derived from Navajo Sandstone are found in the Navajo and Kayenta units here. Further outward, the rock units flatten at the axis of an encircling monocline. This monocline is the outermost structure associated with Upheaval Dome. The region outward from the monocline is characterized by essentially flat-lying strata.

Our map data agree with those reported by Schultz-Ela *et al.* (1994) and Jackson *et al.* (1998), who interpret their data to support the passage of a salt diapir through the dome. However, the structures seen in the dome are remarkably similar to those found in known complex impact craters (*e.g.*, Wilshire *et al.*, 1972; Offield and Pohn, 1979; Shoemaker and Shoemaker, 1996). Below, we describe the structural features of Upheaval Dome in more detail. Localities referred to in the text are shown on Figure 6.

Faults

Recognition of faults during mapping was relatively straightforward for the Chinle Formation and lower rock units, largely due to the tabular bedding geometry and numerous marker beds. Fault recognition was a more involved task in the Wingate and higher units, mainly because these units lack tabular bedding and marker beds. Instead, lenticular bedding and cross-bedding are widespread and cause some bed contacts to look superficially like faults. Gradational interfingering bedding relations exist at both Navajo/Kayenta and Kayenta/Wingate contacts, making bed-subparallel faults difficult to detect at these contacts. In cases where obvious bedding displacement could not be discerned in these units, criteria such as the presence of gouge, breccia, striae, drag folds and high-angle ($> \sim 35°$) bed cutoffs were used to map faults. Unfortunately, these features are not that common. Low-angle ($< \sim 35°$) bed cutoffs alone were not used as a criterion because they are common depositional features in undeformed sections of these units. As a result of the difficulties described above, a conservative approach to fault mapping was adopted for the Wingate to Navajo units, implying that there may be more faults in these units than shown on Plate 1.

Faults are found throughout Upheaval Dome, and increase in density toward the center (Plate 1). Displacement estimates for the faults shown on Plate 1 range from about 5 to 500 meters, with the largest offsets occurring on the outer faults. In the center, faults with mappable displacement (>5-10 meters offset) are spaced about 10 to 50 meters apart and are associated with chaotic structure and highly variable bedding attitudes. Throughout the structure, gouge, breccia, fault striae, and drag folds are developed only sporadically. The scarcity of gouge, breccia, and striae is surprising and implies relatively low friction during displacement. Striae are particularly uncommon in the slope-forming, fine-grained units such as the Chinle and Moenkopi Formations. Thin- to medium-bedded Kayenta, Chinle, Moenkopi, and White Rim strata are generally much more faulted than the thick-bedded to massive Wingate and Navajo Sandstones.

Rock units in general are structurally thickened by repetition along faults in the central area and structurally thinned by faults in the outer area (Fig. 7). This observation implies that Upheaval Dome is characterized by low-angle normal faults in the perimeter and thrust faults in the central area (Fig. 3, Plate 1). There are, however, some places in the central area where the Chinle Formation is structurally thinned. Kinematic data from offset bedding, drag folds, and fault striae indicate dominantly centerward vergence on both normal and thrust faults, but some thrusts display outward vergence or show displacement approximately parallel to a circumferential segment (Fig. 8). There is a notable absence of cross-cutting relations between these variably verging thrusts. Along Upheaval Canyon (the breach west of the dome center), bed-parallel faults that omit section can be traced into rising thrust faults on the flank of the central uplift (Fig. 9, Plate 1). Near the perimeter, there are listric normal faults that locally show reverse drag (*e.g.*, Fig. 7B) or trap-door structures (*e.g.*, south-southeast perimeter, Plate 1). Some faults that have facilitated omission of strata die out along bedding planes rather than ramp up section as they are traced into undeformed rocks (Fig. 10). In places, these faults seem to have facilitated centerward motion of a fault-bounded wedge of rock (Fig. 11). Alternatively, there is the possibility that two episodes of faulting may have occurred, the first of which involved top-away-from-the-center motion. However, in areas where there is physical continuity of exposure between these fault zones and the undeformed perimeter (*e.g.*, the north-northeast, northwest, and southeast perimeters), the regions where these faults die out show no pile-up or folding of strata in the hanging wall, and throughout the map area there are no cross-cutting relations to suggest two episodes of faulting. For these reasons, we favor the hypothesis that a fault-bounded wedge of rock in the footwall of these faults has moved toward the center relative to the hanging wall. It appears that, in addition to structural thinning by listric normal faulting, there is a component of thinning by wedge faulting. Some of the listric normal faults are connected to the wedge-fault systems (Fig. 12). Generally the listric normal faults are structurally above the wedge faults, but in the south-southeast perimeter the listric faults and trap-door structure in the Navajo can be traced southwest along strike into a wedge-fault system.

Folds

Folds of many scales and orientations are expressed throughout Upheaval Dome (Plate 1). Half-wavelengths vary from 0.5 centimeter to 1 kilometer, and fold axis orientations are generally circumferential (parallel to circumferential segments drawn around the center) or radial (parallel to radii drawn outward from the center). The largest folds have circumferential axial traces and are: 1) a monocline that delimits the boundary between Upheaval Dome and the surrounding nearly flat-lying strata, and 2) a syncline lying in the region of transition between normal and thrust faulted areas. Curiously, the monocline is not found everywhere around the structure. In the north-northeast perimeter, the monocline is seen only in Kayenta Formation, where it is associated with small normal faults (Plate 1). In the northeast and south-southeast perimeters, it is found only in the hanging wall of faults that cut the Church Rock Member and die out in bedding planes at the perimeter (*e.g.*, Figure 10). This suggests that the monocline formed either before these faults or as a result of the faulting. The latter interpretation is favored because an early-formed monocline in the footwall of these faults would have been transported centerward relative to the hanging wall, yet there is no deformation in the footwall Moenkopi and lower Chinle units. There is the possibility that similar faults exist at the base of the monocline elsewhere in the map area, but lie below the present level of exposure and also die out along bedding planes rather than ramp upward in the perimeter.

Smaller folds with half-wavelengths on the order of tens of meters are well exposed in the Wingate Sandstone cliff and are dominantly closed, upright folds of radial orientation (Fig. 13). Similar-scale radial open folding of faults in the nearby Kayenta Formation suggests that this folding postdates the faulting, but in places these folds appear to be truncated by faults. Even smaller, outcrop-scale folds are common in the Kayenta Formation, and are present to a lesser extent in the Chinle and Moenkopi Formations. These folds are open to isoclinal, upright to inclined, and are approximately circumferential or radial in orientation. Radial folds of all scales generally plunge away from the center. Circumferential folds in the Kayenta Formation are in places asymmetric or show drag where related to faults. Where discernible, centerward vergence is usually indicated, but a few folds record outward vergence. No cross-cutting relations were found between these two types of verging folds. Presence of drag folds and absence of folded faults in the outcrop-scale folds suggests that these folds formed contemporaneously with or prior to the faults.

Clastic dikes

Clastic dikes are found throughout Upheaval Dome in all rock units and comprise roughly 2-20% of the outcrops. High percentages of dikes are found in the center of the structure and their number decreases radially outward (Fig. 8). Cross-cutting relations show that at least some of the dike injection preceded faulting (Fig. 14A), but the occurrence of dikes along fault planes indicates synkinematic to post-kinematic injection. No systematic orientation of dikes is apparent. In most cases, the dikes have been injected along faults and tensional fractures, and range in thickness from less than a centimeter to several meters. A few appear to have flowed into the host rock without the aid of a fracture. These dikes have contorted flow structure and contacts that are lobate or resemble flame structures, suggesting local plastic or fluid behavior of the host rock during emplacement (Fig. 14B). At the base of the Wingate cliff near the center, beds of the Church Rock Member are locally shoved upward into fluidized Wingate Sandstone, which has in turn flowed downward as dikes into the Church Rock Member. In some places at the base of the cliff, lobate masses of Wingate Sandstone apparently flowed centerward and overlap the Church Rock Member.

The dikes are composed of orange, red, or white quartzose sandstone. White dikes are found mainly in the center of the dome and the orange and red dikes occur near the center to the perimeter of the dome. Orange-colored dikes in the Chinle Formation have in some cases been physically traced to sources at the base of the Wingate Sandstone, but in general, protoliths for the clastic dikes are inferred on the basis of color, mineralogy, and the assumption that they are not far-traveled. Thus, white dikes in the center were derived from the White Rim Sandstone; orange dikes in the Kayenta Formation are from the Wingate Sandstone or Navajo Sandstone, and the orange dikes in the Navajo Sandstone and red dikes in the Kayenta Formation are derived from the formations in which they occur.

In thin section, dike samples show a broad range of grain fracturing. The most highly fractured grains are seen in samples from the center of the dome (Fig. 15). Planar deformation features indicative of shock are not obvious in the dike samples that we examined, but have been reported to exist in a White Rim dike sampled and studied by Unger (1995). Further study is underway to confirm the presence of these features.

Interpretation of Structural Features

Displacement along normal faults and structural thinning of strata in the perimeter, and occurrence of thrust faults, radial folds, and structurally thickened strata in the center demonstrate motion of rock from the perimeter toward the center of the structure (Fig. 16). The subsidiary outward verging structures are interpreted to be back-thrusts and back-folds formed during this centerward motion, although a separate (early?) stage of minor outward-verging deformation cannot be ruled out. As shown by continuous exposure in Upheaval Canyon, the normal and thrust faults are coeval and connected components of a listric fault system that facilitated gravitational sliding of rocks toward the center (Plate 2). Some centerward motion of fault-bounded wedges evidently also occurred on subhorizontal faults that conjoin and die out within horizontal bedding near the perimeter of the structure. The lack of monoclinal folding in the footwall of these faults implies that the large-scale circumferential syncline and monocline were formed chiefly by fault removal of underlying Kayenta to White Rim units from these areas. Some of the synclinal folding could also be due to relatively minor flow of salt at depth (Plate 2). This syncline is interpreted to be the ring structural depression of a complex crater.

The prevalence of faults in the dome illustrates that the rocks largely behaved brittley during impact and subsequent gravitational sliding, but the occurrence of folds and clastic dikes indicates some fluid to plastic behavior. Massive to thick-bedded, relatively homogeneous formations such as the Wingate Sandstone and Navajo Sandstone appear to be relatively free of faults, whereas thinner-bedded, lithologically heterogeneous formations are cut by numerous faults. Local plastic to fluid behavior of the Wingate and, to a lesser extent, other units may be due to the presence of fluids and/or a low degree of lithification, since the deformation in many places resembles that seen in soft-sediment landslides. Fluid presence could also account for the relatively low frictional resistance characteristic of much of the fault displacement.

In summary, the development of Upheaval Dome began with fracture and local fluidization (clastic diking) of rocks during impact, followed by convergent flow of brittle to plastic material toward the center and some continued emplacement of clastic dikes. This convergent flow formed the central uplift and ring structural depression.

IMPACTITES

A lag deposit of resistant quartzose cobbles occurs in patches and as individual fragments scattered along a minor drainage within the ring structural depression, near its eastern margin. Their exact location is not shown in this paper, as requested by Canyonlands National Park officials. The cobbles rest on the Navajo Sandstone and on alluvium and wind-blown sand derived from the Navajo (Fig. 17). The areal extent of the deposit is approximately 300 × 400 meters. Based on the evidence presented below, we interpret these cobbles to be "impactites" formed by cooling and solidification of impact melt.

Much of the impactite material is in the form of rounded cobbles 5 to 15 centimeters in diameter, but many angular fragments and broken cobbles are also present. Where they are broken open, the large cobbles are found to be stream-worn or wind-abraded vesicular bombs with nonvesicular to weakly vesicular quenched rims (Fig. 18A). Although they are now largely crystalline, these objects appear to have been once partly and perhaps largely molten. A few bombs have stubby tails possibly formed in the process of pull apart and break up of impact melt (Fig. 18B). Some impactites are dense or have few vesicles, and some of the dense specimens are strongly flow-banded. All of the impactites that we have examined so far are composed predominantly of quartz and evidently are derived from quartz arenite protoliths. The vesicles are lined with tiny euhedral quartz crystals. Thin sections that we have examined revealed little or no glass, although some of the rock is sufficiently fine grained to impede easy identification under the microscope (Fig. 18C). The impactites seem to be entirely or almost entirely recrystallized to polygonal-textured quartz, and planar deformation features appear to be absent. Additional work is in progress to confirm the impact origin of these interesting rocks through further characterization of the phases present and determination of major and trace element concentrations.

SHATTER SURFACES AND SHATTER CONES

Shatter cones are conical fracture surfaces decorated with "fan-tailed" patterns of ridges and grooves that diverge away from the apices of the cones. They were first recognized at the Steinheim Basin, Germany (Branco and Fraas, 1905) and have been found at many other, but not all, impact structures (Dietz, 1963, 1968). They also have been produced by high speed impact experiments and by detonation of chemical and nuclear explosives (Shoemaker *et al.*, 1961; Bunch and Quaide, 1968; Schneider and Wagner, 1976; Roddy and Davis, 1977). Milton (1977) estimated that shatter cones may be formed over a range of shock pressures from about 2.5 to 25 gigapascals.

Shatter cones were reported by Shoemaker *et al.* (1993) in thin sandstone beds of the Moenkopi Formation near the center of Upheaval Dome. These cones are rare and not as finely decorated and grooved as shatter cones found at many other impact structures (Fig. 19). In places on the central uplift, however, thin beds of siltstone and very fine sandstone of the Moenkopi are pervasively cut by roughly planar fractures decorated with fan-tailed patterns of grooves and ridges. We refer to these fractures as "shatter surfaces." Generally, the shatter surfaces are inclined at angles of about 45° to

60° to the bedding. Multiple sets of shatter surfaces are present in individual beds. Locally, shatter surfaces can be traced with varying strike over arcs with radii of curvature of tens of centimeters. The shatter surfaces along these arcs appear to be segments of large cones whose apices point stratigraphically upward. We suggest that the shatter surfaces observed at Upheaval Dome have been formed in response to shock pressures within the lower part of the range over which typical shatter cones are formed.

DISCUSSION AND CONCLUSION

Detailed geologic mapping at Upheaval Dome has yielded several lines of evidence for an impact origin. The structure of Upheaval Dome corresponds to that expected for a complex crater. The pattern of faulting, folding, and clastic dike injection at Upheaval Dome resembles that seen in other known impact structures, and is particularly similar to that of the Sierra Madera structure, southwest Texas (Wilshire *et al.*, 1972). Shock effects include shatter cones and shatter surfaces and impactite fragments and bombs.

Shoemaker and Herkenhoff (1984) suggested that, since the time of impact, one to two kilometers of strata might have been removed from the vicinity of Upheaval Dome and that the crater likely was formed in late Cretaceous or Paleogene time. Their suggestion implied that the crater-like head of Upheaval Canyon, located in the center of Upheaval Dome, is strictly the result of differential erosion long after the impact structure was formed. Our subsequent discovery of an impactite lag deposit and reexamination of unusual lobes of Wingate Sandstone along the walls of Upheaval Canyon now lead us to a somewhat different perspective on the depth of erosion and age of the impact structure.

The discovery of eroded impactite bombs resting on Navajo Sandstone within the ring structural depression was a complete surprise. Even though these quartzose cobble-size objects are much more resistant to weathering than the Navajo Sandstone or other higher sandstone formations that might have been present at the time of impact, it is difficult to imagine that the land surface where they are found could have been denuded more than 100 or 200 meters before the impactites were entirely washed away. Indeed, the impactites may have been initially deposited on a surface directly underlain by the Navajo Sandstone.

The maximum extent of the listric faults that bound the structure defines a final crater diameter of at least 5 km. Dence *et al.* (1977) found that, for terrestrial craters larger than 2.4 km in diameter in crystalline rocks, the rim diameter D is related to the impact energy E by

$$D = 1.96 \times 10^{-5} E^{1/3.4}$$

where D is in kilometers and E is in joules. Assuming that the energy for sedimentary rocks is 20% less that the energy for crystalline rocks (Dence *et al.*, 1977), the kinetic energy of the impactor that formed Upheaval Dome was at least 2.4×10^{18} J. For an impact velocity of 20 km/sec, this corresponds to an impactor mass of 9.7×10^{9} kg. Asteroid densities vary between 2200 and 8000 kg/m^3 (Wetherill, 1977), implying that an asteroidal impactor would have been between 100 m and 170 m in radius. Comets have much lower densities, but generally impact Earth at higher velocities, so the size of a cometary impator would be similar. If there has been substantial erosion of the impact structure since it formed, somewhat larger impactors would be indicated. The amplitude of the structural uplift, U, is given approximately by

$$U = 0.06D^{1.1}$$

where D is the final crater diameter in kilometers (Grieve *et al.*, 1981; Grieve, 1991). For a crater of 5 km diameter, the expected uplift is approximately 350 meters. Hence, the observed structural uplift at Upheaval Dome is consistent with the scaling relationship derived from other terrestrial impact craters.

Lobate or tongue-like structurally coherent masses of Wingate Sandstone and adjacent beds of the upper Chinle Formation occur low on the wall of the crater-like topographic feature at the head of Upheaval Canyon. At least one of these masses is displaced down the wall across lower beds of the Chinle along a contact that is roughly parallel with the wall. Elsewhere, one of the Wingate lobes penetrates into the underlying Chinle. We suggest that these lobes may represent partly fluidized sandstone that slumped along the walls of the initial transient cavity. If so, the walls of the present topographic crater must be close to the final position of the transient cavity walls after their inward migration during crater collapse. This inner, constricted crater has been breached on the west side and all strongly shocked rocks evidently have been removed from the center by erosion. The total erosion of the center, however, might be no more than a few hundred meters, sufficient to remove any deposits filling the initial crater and any strongly shocked material and to produce the highly dissected central topography we see today.

The deep canyons in the landscape surrounding Upheaval Dome and incised into the impact structure have been cut subsequent to impact. This episode of canyon cutting is no older than integration of the upper with the lower Colorado River drainage at about 5 Ma and the cutting of the lower Grand Canyon (Lucchitta, 1972). Recent work suggests that deep canyon cutting in the center of the Colorado Plateau, upstream from the Grand Canyon, has occurred chiefly in the last half million years (Lucchitta *et al.*, 1994). Upheaval Dome probably has been formed late in the history of denudation of the central Colorado Plateau, possibly as late as a few million years ago. It is also possible that the impact occurred in the Jurassic not long after deposition of the Navajo Sandstone. Isotopic studies of the impactites at the U. S. Geological Survey and fission-track investigations at the University of Pennsylvania of shocked apatite from the center of the Dome are currently underway to further constrain the age of Upheaval Dome.

Our field study of Upheaval Dome has permitted us to examine the mechanical behavior of rocks and the kinematics of structures associated with collision and subsequent formation of the central uplift and ring structural depression in sedimentary target bodies. It appears that even at relatively shallow depth below the transient crater and zone of impact melting, planar deformation features are not well developed in sedimentary rocks. Shatter cones are only weakly developed in the particular rock types present at Upheaval Dome. Brittle fracture and clastic diking are the most easily recognized response to the stresses induced by impact. Similar clastic dikes at the Roberts rift may also be due to impact (Huntoon and Shoemaker, 1995), but this hypothesis does not explain the apparent absence of dikes in the area between the dome and the rift. The clastic dikes at Upheaval Dome may be related in origin to pseudotachylite dikes seen in other complex craters. Following impact, centerward flow along listric faults, accompanied by some fault wedging, plastic folding, and additional clastic diking, has produced the central uplift and part, if not all, of the ring structural depression. Early fracture upon impact may have facilitated introduction of fluids into the faults and thus reduced frictional resistance to gravitational sliding. The listric normal faults at the perimeter of the dome are of lower dip angle than those inferred to bound slumped terraces on the walls of lunar complex craters, but have similar sense-of-shear and are considered to be coeval with terrace development.

ACKNOWLEDGMENTS

Thanks are extended to the National Park Service and all of the field assistants who helped with logistical aspects of the field work. This project was funded by the NASA Planetary Geology and Geophysics Program.

REFERENCES CITED

Boon, J. D., and C. C. Albritton, Jr., Established and supposed examples of meteoritic craters and structures, *Field and Laboratory, 6*, 44-56, 1938.

Branco, W., and E. Fraas, Das kryptovulcanische Becken von Steinheim, *Akademie der Wissenschaften Berlin, Phys.-math. Kl, Abh. 1*, 64 p., 1905.

Bucher, W. H., Cryptovolcanic structures in the United States, *International Geological Congress, 16th, Washington, D.C., 1933, Report, v. 2*, 1055-1084, 1936.

Bunch, T. E., and W. L. Quaide, Shatter cones in the Danny Boy nuclear crater, in *Shock Metamorphism of Natural Materials*, edited by B.M. French and N.M. Short, p. 285, Mono Book Corp., Baltimore, 1968.

Cater, F. W., Geology of the salt anticline region in southwestern Colorado, *U.S. Geol. Surv. Prof. Pap. 637*, 80 p., 1970.

Dence, M. R., R. A. F. Grieve, and P. B. Robertson, Terrestrial impact structures: Principal characteristics and energy considerations, in *Impact and Explosion Cratering*, edited by D.J. Roddy, R.O. Pepin, and R.B. Merrill, pp. 247-275, Pergamon Press, New York, 1977.

Dietz, R. S., Astroblemes: ancient meteorite-impact structures on the Earth, in *The Moon, Meteorites and Comets*, edited by B.M. Middlehurst and G.P. Kuiper, pp.285-300, University of Chicago Press, Chicago, 1963.

Dietz, R. S., Shatter cones in cryptoexplosion structures, in *Shock Metamorphism of Natural Materials*, edited by B.M. French and N.M. Short, pp. 267-285, Mono Book Corp., Baltimore, 1968.

Doelling, H. H., C. G. Oviatt, and P. W. Huntoon, Salt deformation in the Paradox region, *Utah Department of Natural Resources Bulletin 122*, 93 p., 1988.

Grieve, R. A. F., P. B. Robertson, and M. R. Dence, Constraints on the formation of ring impact structures, based on terrestrial data, in *Multi-ring Basins*, edited by P. H. Schultz and R. B. Merrill, pp. 37-57, Pergamon Press, New York, 1981.

Grieve, R. A. F., Terrestrial impact: the record in the rocks, *Meteoritics, 26*, 175-194, 1991.

Harrison, T. S., Colorado-Utah salt domes, *Am. Assoc. Petrol. Geol. 11*, 111-133, 1927.

Huntoon, P. W., G. H. Billingsley, Jr., and W. J. Breed, Geologic map of Canyonlands National Park and vicinity, Utah, *Canyonlands Natural History Association*, Moab, Utah, 1982.

Huntoon, P. W., and E. M. Shoemaker, Roberts Rift, Canyonlands, Utah, a natural hydraulic fracture caused by comet or asteroid impact, *Ground Water, 33*, 561-569, 1995.

Jackson, M. P. A., R. R. Cornelias, C. H. Craig, A. Gansser, J. Stocklin, and C. J. Talbot, Salt diapirs of the Great Kavir, Central Iran, *Geol. Soc. Am. Mem. 177*, 139 p., 1990.

Jackson, M. P. A., D. D. Schultz-Ela, M. R. Hudec, I. A. Watson, and M. L. Porter, Upheaval dome as a pinched-off salt diapir: An alternative to the impact hypothesis, submitted to *Geol. Soc. Am. Bull.*, 1998.

Joesting, H. R., and D. Plouff, Geophysical studies of the Upheaval Dome area, San Juan County, *Utah Intermountain Assoc. Petrol. Geol., 9th Annual Field Conf.*, 86-92, 1958.

Kriens, B. J., E. M. Shoemaker, and K. E. Herkenhoff, Structure and kinematics of a complex impact crater, Upheaval Dome, southeast Utah, in *Geological Society of America Field Trip Guidebook, 1997 Annual Meeting, Salt Lake City, Utah*, edited by P. K. Link and B. J. Kowallis, pp. 19-31, Brigham Young University Geology Studies, v. 42, part II, Provo, Utah, 1997.

Louie, J. N., S. Chavez-Perez, and G. Plank, Impact deformation at Upheaval Dome, Canyonlands National Park, Utah, revealed by seismic profiles (abstract), *Eos Trans. AGU 76*, 337, 1995.

Lucchitta, I., Early history of the Colorado River in the Basin and Range province, *Geol. Soc. Am. Bull., 83*, 1933-1948, 1972.

Lucchitta, I., M. Caffee, R. C. Finkel, G. Curtis, M. Davis, S. Davis, T. C. Hanks, and B. D. Turrin, Quaternary alluvial chronology in the eastern Grand Canyon-Lake Powell region, Arizona and Utah (abstract), *Geol. Soc. Am. Abstr. Prgrms., 26*, A-258, 1994.

McCleary, J. R., and J. E. Romie, Stratigraphic and structural configuration of the Navajo (Jurassic) through Ouray (Mississippian-Devonian) Formations in the vicinity of Davis and Lavender Canyons, southeastern Utah, *Technical Report ONWI-594*, 187 pp., Woodward-Clyde Consultants, prepared for Office of Nuclear Waste Isolation, Batelle Memorial Institute, Columbus, Ohio, 1986.

McKnight, E. T., Geology of area between Green and Colorado Rivers, Grand and San Juan Counties, Utah, *U. S. Geological Survey Bulletin 908*, 147 pp., 1940.

Milton, D. J., Shatter cones - An outstanding problem in shock mechanics, in *Impact and Explosion Cratering*, edited by D. J. Roddy, R. O. Pepin, and R. B. Merrill, pp. 703-714, Pergamon Press, New York, 1977.

Offield, T. W., and H. A. Pohn, Geology of the Decaturville impact structure, Missouri, *U. S. Geological Survey Professional Paper 1042*, 48 pp., 1979.

Roddy, D. J., and L. K. Davis, Shatter cones formed in large-scale experimental explosion craters, in *Impact and Explosion Cratering*, edited by D. J. Roddy, R. O. Pepin, and R. B. Merrill, pp. 715-750, Pergamon Press, New York, 1977.

Schneider, E., and G. A. Wagner, Shatter cones produced experimentally by impacts in limestone targets, *Earth and Planetary Science Letters, 32*, 40-44, 1976.

Schultz-Ela, D. D., M. P. A. Jackson, M. R. Hudec, R. C. Fletcher, M. L. Porter, and I. A. Watson, Structures formed by radial contraction at Upheaval Dome, Utah, *Geol. Soc. Am. Abstr. Prgrms., 26,* A-72, 1994.

Shoemaker, E. M., Structural features of southeastern Utah and adjacent parts of Colorado, New Mexico, and Arizona, in *Guidebook to the Geololgy of Utah, 9,* edited by W. L. Stokes, pp. 48-69, Utah Geol. Soc., 1954.

Shoemaker, E. M., Structural features of the central Colorado Plateau and their relation to Uranium deposits, *U. S. Geological Survey Professional Paper 300,* 155-170, 1956.

Shoemaker, E. M., Penetration mechanics of high velocity meteorites, illustrated by Meteor Crater, Arizona, *Report, pt. 18, International Geological Congress, 21st,* pp. 418-434, Copenhagen, 1960.

Shoemaker, E. M., Asteroid and comet bombardment of the Earth, *Ann. Rev. Earth and Planet. Sci., 11,* 461-494, 1983.

Shoemaker, E. M., D. E. Gault, and R. V. Lugn, Shatter cones formed by high speed impact in dolomite, *U. S. Geological Survey Professional Paper 424-D,* 365-368, 1961.

Shoemaker, E. M., and K. E. Herkenhoff, Impact origin of Upheaval Dome, Utah (abstract), *Eos Trans. AGU, 64,* 747, 1983.

Shoemaker, E. M., and K. E. Herkenhoff, Upheaval Dome impact structure (abstract), *Lunar and Planetary Science XV,* 778-779, 1984.

Shoemaker, E. M., K. E. Herkenhoff, and V. A. Gostin, Impact origin of Upheaval Dome, Utah (abstract), *Eos Trans. AGU, 74,* 388, 1993.

Shoemaker, E. M., and C. S. Shoemaker, The Proterozoic impact record of Australia, *Jour. Australian Geol. Geophys., 16,* 379-398, 1996.

Stewart, J. H., F.G . Poole, and R. F. Wilson, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region, *U. S. Geological Survey Professional Paper 691*, 195 pp., 1972.

Unger, M., Geology and Structure of Upheaval Dome, San Juan County, Utah: Salt or Impact Structure?, Senior Integrative Exercise, Carleton College, Northfield, Minnesota, 77 pp., 1995.

Wetherill, G. W., The nature of the present interplanetary crater-forming projectiles, in *Impact and Explosion Cratering*, edited by D.J. Roddy, R.O. Pepin, and R.B. Merrill, pp. 613-615, Pergamon Press, New York, 1977.

Wilshire, H. G., T. W. Offield, K. A. Howard, and D. Cummings, Geology of the Sierra Madera cryptoexplosion structure, Pecos County, Texas, *U. S. Geological Survey Professional Paper 599-H*, 42 pp., 1972.

Worrall, D. M., and S. Snelson, Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt, in *The Geology of North America-An Overview*, edited by A. W. Bally and A. R. Palmer, pp. 97-138, Geol. Soc. Am., Boulder, Colorado, 1989.

FIGURE CAPTIONS

Figure 1. Map of Utah, showing location of Upheaval Dome.

Figure 2. Landsat TM image of SE Utah, showing area in the vicinity of Moab and Canyonlands National Park (cf. Figure 1). North is up, resolution is 30 m/pixel. Most of the area is underlain by essentially flat-lying strata. Also clearly visible are NNE-striking Grabens area normal faults in bottom center of image. The salt diapirs found in the Colorado River drainage are too small to be seen here. Also shown are the locations of the Cane Creek anticline and Shafer dome (a broad, doubly plunging anticline), interpreted

by Cater (1970) as salt structures, and the Roberts rift. Image courtesy Chris Lee, annotated by Tim Parker.

Figure 3. Simplified geologic map of Upheaval Dome, compiled from mapping at 1:6,000 (Plate 1). Also shown is location of drill hole Buck Mesa #1, Husky Oil Company.

Figure 4. Oblique aerial photograph of Upheaval Dome, looking NW, for comparison with geology in Figure 3. Road at bottom of photo, and general topography, can be used for matching with Figure 3. From center outward, major rock units are: 1) White Rim Sandstone and Moenkopi Formation (light- to dark-colored central topographic high), 2) Chinle Formation (slopes below inner cliff), 3) Wingate Sandstone (inner cliff), 4) Kayenta Formation (circular moat between inner and outer cliffs), and 5) Navajo Sandstone (outer circular belt of light-colored cliff-forming rocks). Pronounced topographic high in center is associated with structural uplift of about 350 m. Ring structural depression (circumferential syncline) is visible in Navajo Sandstone at upper right side of photo. Upheaval Canyon is visible at upper left and drains center of the dome. Dark swath in uppermost left is Green River. Location of closest undeformed section used in Figure 5 is below prominent cliff on south side of Upheaval Canyon, upper left side of photo. Photo courtesy of Tom Till.

Figure 5. Composite stratigraphic column showing rock units and thicknesses in undeformed region around perimeter of Upheaval Dome. Column was constructed from three sources: 1) gamma log located near Willow Flat campground, approximately 5 km SE of Upheaval Dome (Murphy Range Unit No. 1, Pan American Petroleum Corp., reproduced in McCleary and Romie, 1986), 2) stratigraphic observations of Moenkopi Formation at W end of Steer Mesa, about 4 km WSW of Upheaval Dome (Stewart *et al.*, 1972), and 3) stratigraphic field study of Chinle and Moenkopi Formations exposed on the

S side of Upheaval Canyon, approximately 1 km WNW of deformed rocks at Upheaval Dome (mapped in 1997, see Figure 4). Older Paleozoic rocks and pre-Cambrian crystalline basement lie below Paradox Formation but are not shown here. Top of Navajo Sandstone not exposed in or around Upheaval Dome, but estimated thickness (based on closest exposure) is shown with dashed line.

Figure 6. Locality map, showing place names and most photograph locations.

Figure 7. Photographs of faults. See Figure 6 for locations. (A) Thrust fault in Kayenta Formation. View looking W at top-toward-the-center vergence. On smaller scale, some top-away-from-center vergence is also visible above main fault. (B) Low-angle normal faults exposed in SW perimeter of dome. View to NW, center of dome lies to right of photo. One fault system can be seen dipping NE and cutting down through cliff of Wingate Sandstone (w). Note Kayenta (k)-Wingate contact (bedded Kayenta Formation in rubble-covered slope above Wingate cliff) offset by top-toward-the-center displacement. Navajo Sandstone (n), exposed in upper cliff and much of background, is also in fault contact with the Kayenta Formation. Note that Kayenta Formation has been significantly thinned by offset on both faults and, although difficult to see here, Navajo Sandstone displays reverse drag of bedding at southernmost end of upper cliff in foreground (cf. Plate 1). Note monocline visible in background. Scale of foreground in photo is roughly 250 x 500 m. (C) View looking NE from center of dome at faulted and duplicated Moenkopi Formation of central topographic high. Clastic dike of White Rim Sandstone visible at lower right. Scale ~ 80 m x 250 m.

Figure 8. Map showing kinematic data and locations of clastic dikes. See Plate 1 for corresponding attitudes of faults.

Figure 9. Looking N at cliff showing thrust faults in Kayenta Formation (k) and Wingate Sandstone (w). Motion inferred to be top-toward-center. Navajo Sandstone (n) in background lies concordantly on Kayenta Formation, but contact is not visible here. Scale of photo ~ 250 m x 550 m.

Figure 10. View looking WNW at fault in Chinle Formation. See Figure 6 for location and Figure 8 for additional kinematic data from the area. Fault shown as dying out at right side of photo as it becomes bed-parallel. Attempts to trace this fault NW into undeformed perimeter reveal that it never ramps up-section but rather dies out in Chinle either here or farther to the NW. Note also that monocline is only developed in hanging wall. Monocline appears to have formed in response to faulting, which may have facilitated centerward motion of a wedge-shaped block of Chinle Formation from the fault zone (compare with Figure 11, located 330 m SE of here). Additional faults (shown as dashed lines) may be present to left of this fault (and connected to it), but are obscured by cover. Unit labels: cr - Church Rock Member, bl - Black Ledge Member, and p - Petrified Forest Member. Scale of photo ~ 250 m x 550 m.

Figure 11. Looking ESE at cliff showing apparent motion of fault-bounded wedge of rock toward center of Upheaval Dome. See Figure 6 for location and Figure 8 for additional kinematic data. Bedding traces within rock units shown with dashed line. Unit labels: n - Navajo Sandstone, k - Kayenta Formation, w - Wingate Sandstone, and cr - Church Rock Member. Basal fault is shown as dying out along bedding, but may continue around corner at left side of photo. Scale of photo ~ 250 m x 600 m.

Figure 12. Looking S at bedding cutoffs in Wingate Sandstone (w) and Church Rock Member (cr) consistent with motion of a wedge of rock toward center (located left of photo). Bed-parallel fault zone at base of Kayenta Formation (k) also shown. See Figure

6 for location and Figure 8 for additional kinematic data. Fault zone at Wingate-Church Rock contact can apparently be traced southward along this contact for 1 km before it ramps up section in the direction of the undeformed perimeter (see Plate 1). About 500 m S, fault-bounded wedge of Wingate Sandstone is linked to both fault zones shown here (see Plate 1). Scale of photo ~ 80 m x 200 m.

Figure 13. Looking NNE at radial folds in basal Wingate Sandstone. Width of view approximately 300 m.

Figure 14. Examples of clastic dikes. (A) Outcrop from perimeter of Upheaval Dome, looking E. W-dipping normal fault at top truncates near-vertical sandstone dike. (B) Looking NW at clastic dike in Kayenta Formation. Hammer rests on country rock, dike is toward right. Note contorted flow structure and lobate contact with country rock.

Figure 15. Photomicrographs of White Rim Sandstone (quartz arenite), crossed polars. Scale of both photos is 2 mm x 3 mm. (A) Sample from undeformed section exposed on Shafer Trail, 10 km ENE of Upheaval dome. Note well-sorted, rounded, and compacted texture. (B) Sample of White Rim Sandstone dike from center of Upheaval Dome. Note pervasive fracturing of grains and resultant increase in angularity and fine-grained matrix.

Figure 16. Diagram showing how convergent flow from perimeter to center causes radial folding and concomitant plastic thickening in Wingate Sandstone. Prior to erosion, Navajo Sandstone may have looked similar to this. In other exposed rock units, similar strain has been accommodated mainly by faulting with some folding. Original drawing by Lottie Soll.

Figure 17. Lag deposit of impactites resting on Navajo Sandstone (light-colored central area of photo) and soil (dark-colored edges of photo). Sunglasses in lower center for scale. Some rounded fragments visible, but most subangular. In nearby stream beds, rounded fragments predominate. Note also dark desert varnish on impactites. Fresh surfaces are light gray to buff.

Figure 18. Eroded impactite bombs from lag deposit on Navajo Sandstone. See Kriens *et al.* (1997) for additional photos of hand samples. (A) Sample (~ 10 cm x 15 cm) shows vesicular interior and quenched rim. (B) Sample (~ 4 cm x 8 cm) has "pull apart" tail at left. (C) Photomicrograph of flow banded impactite (crossed polars). Scale is 2 mm x 3 mm. Fine-grained quartz, opaques, and possibly some glass are present in matrix surrounding nuclei of coarser, polygonal, unstrained quartz. Nuclei may represent devitrification spherulites in advanced stage of recrystallization that typically follows radial growth of quartz in spherulite.

Figure 19. Shatter cone in sandstone of Moenkopi Formation. Scale in cm.

Plate 1. Bedrock geologic map of Upheaval Dome.

Plate 2. Geologic cross-section of Upheaval Dome. Section line shown on Plate 1.

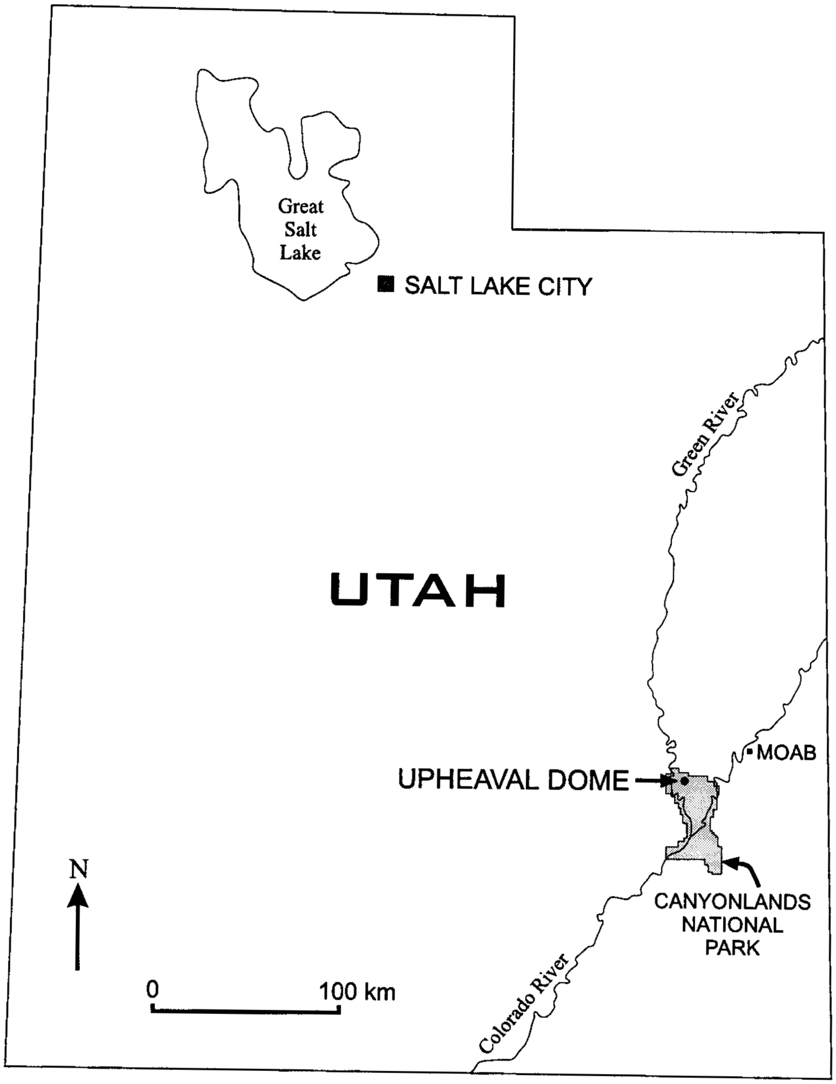

Great
Salt
Lake
SALT LAKE CITY
Green River
UTAH
MOAB
UPHEAVAL DOME
N
CANYONLANDS
NATIONAL
PARK
0
100 km
Colorado River

Fig. 1

Fig. 2

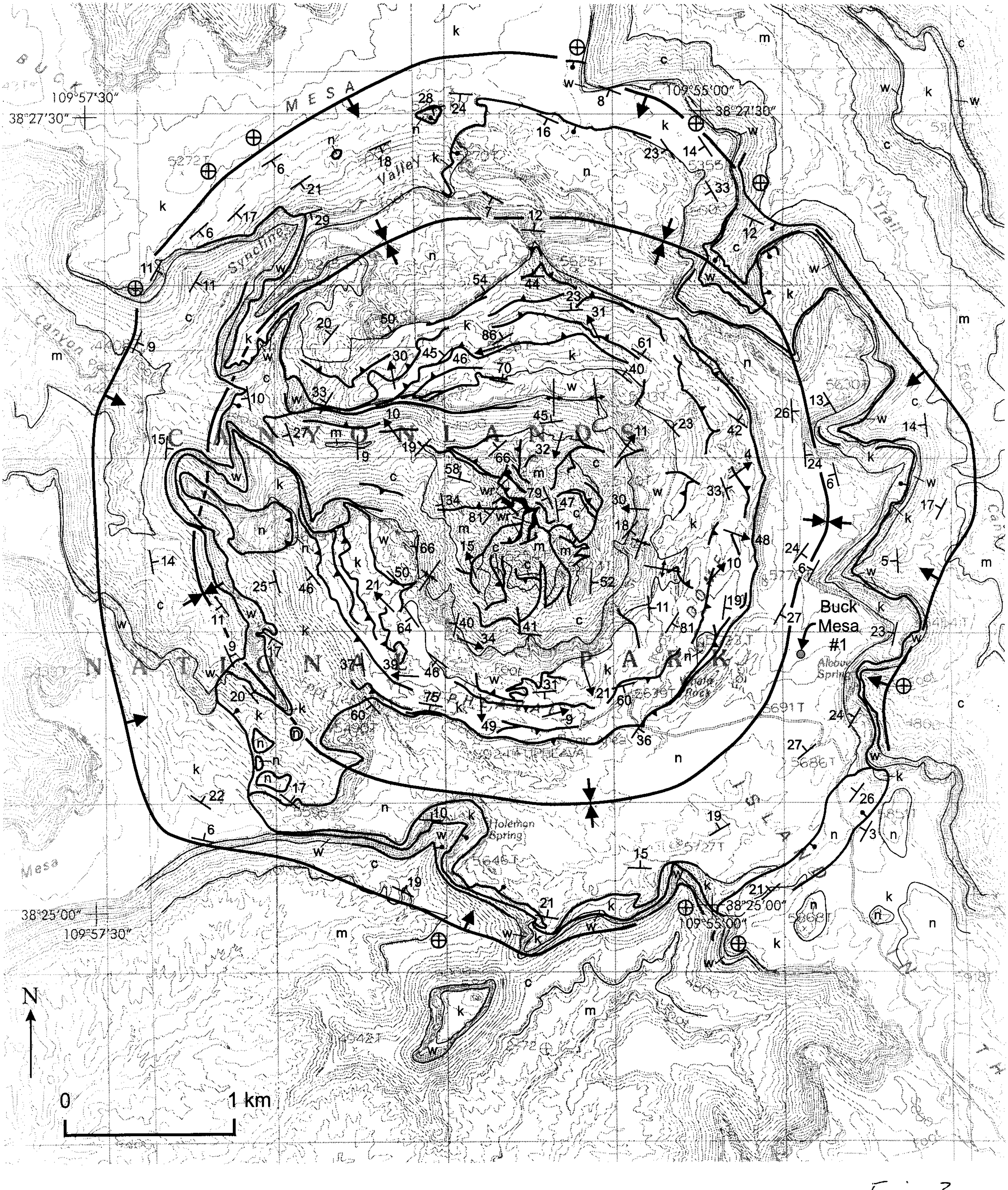

109°57'30"
38°27'30"
109°55'00"
38°27'30"
38°25'00"
109°57'30"
38°25'00"
109°55'00"
MESA
Syncline
Valley
Canyon
CANYONLANDS
NATIONAL
PARK
Buck
Mesa
#1
Holeman
Spring
Whale
Rock
Trail
Mesa
N
0
1 km

Fig. 3

LEGEND

n	Jurassic Navajo Sandstone
k	Jurassic Kayenta Formation
w	Jurassic to Triassic Wingate Sandstone
c	Triassic Chinle Formation
m	Triassic Moenkopi Formation
wr	Permian White Rim Sandstone beds and clastic dikes
	contact, depositional outside of regional monocline, possibly a fault zone in many places elsewhere
	fault
	normal fault, bar and ball on downthrown side
	thrust or reverse fault, teeth on hanging wall
	axial trace of syncline, ½ wavelength on the order of tens of meters
	axial trace of anticline, ½ wavelength on the order of tens of meters
	axial trace of regional syncline
	axial trace of regional monocline
64	strike and dip of bedding
⊕	horizontal bedding
21	trend and plunge of outcrop-scale fold axes

Fig. 3 (cont.)

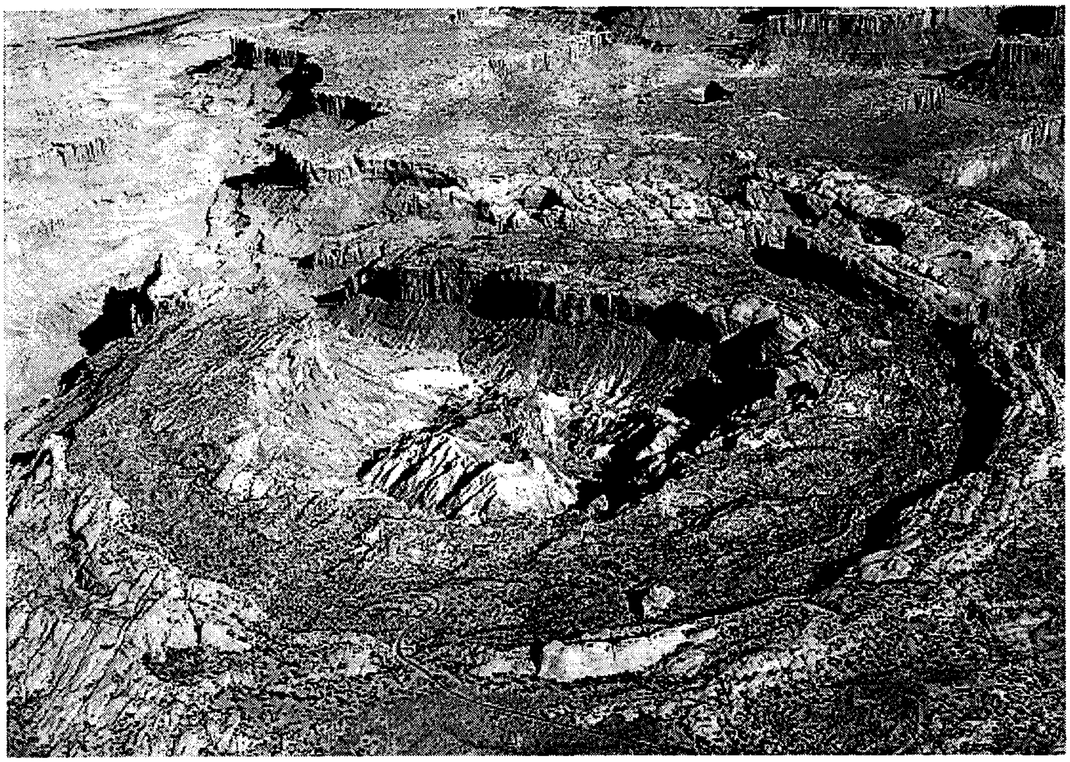


Fig. 4

STRATIGRAPHIC COLUMN OF ROCK UNITS IN THE VICINITY OF UPHEAVAL DOME, CANYONLANDS NATIONAL PARK, UTAH

Map and cross-section rock unit labels are shown in parentheses.

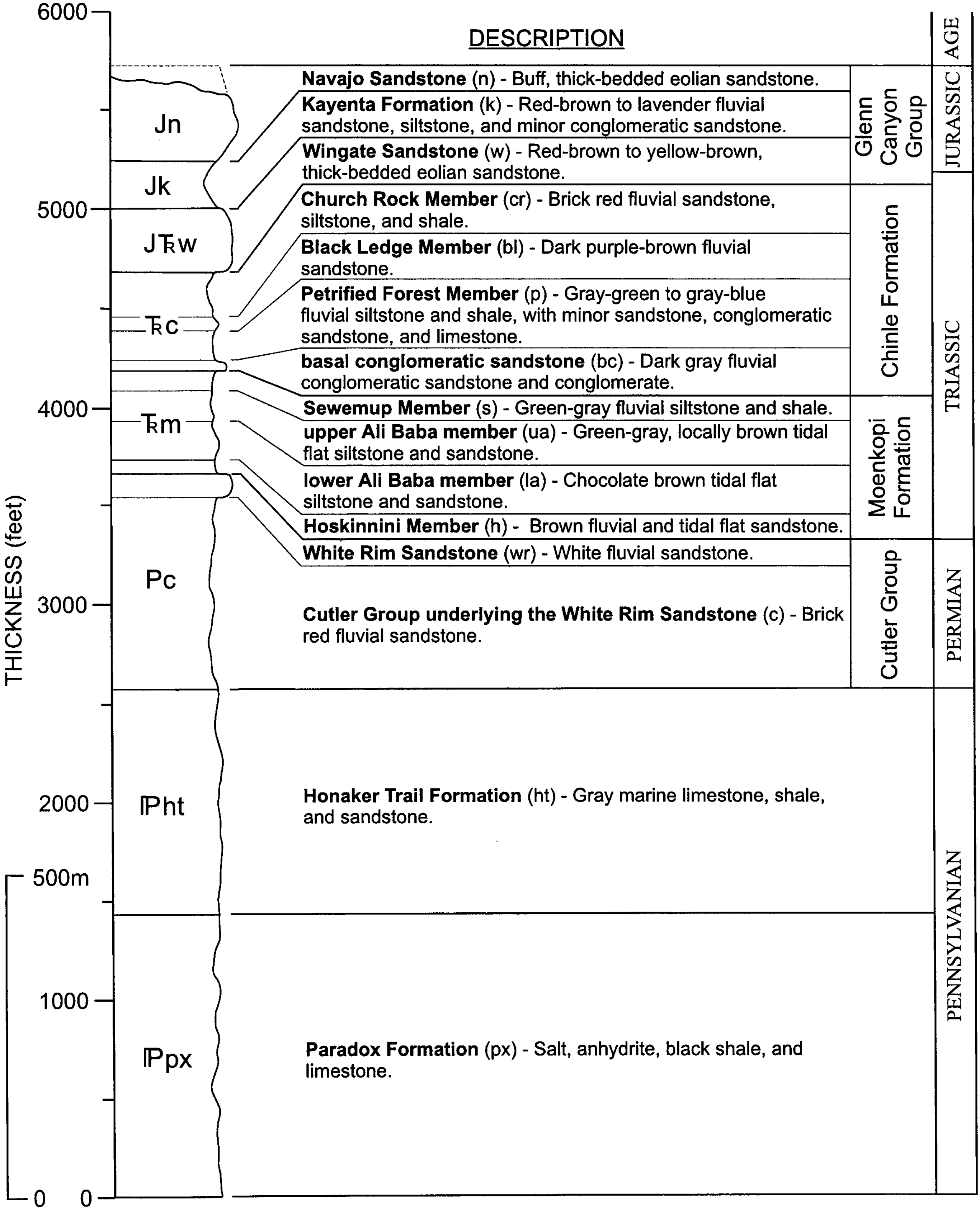
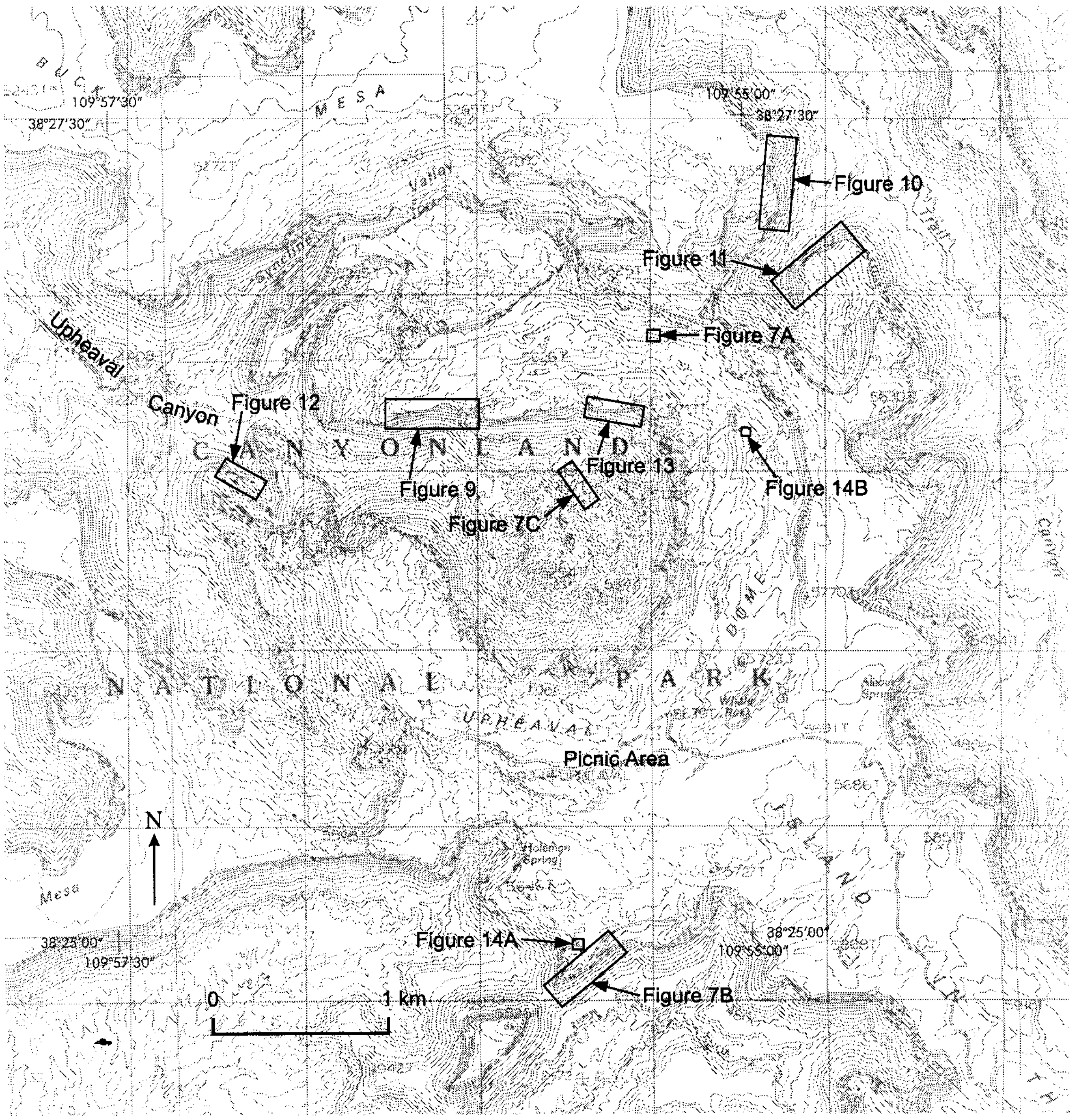


Fig. 5



109°57'30"
38°27'30"
MESA
109°55'00"
38°27'30"
Valley
Figure 10
Figure 11
Syncline
Upheaval
Figure 7A
Canyon
Figure 12
CANYONLANDS
Figure 13
Figure 14B
Figure 9
Figure 7C
DOME
NATIONAL PARK
UPHEAVAL
Picnic Area
N
Mesa
ISLAND
Holeman Spring
38°25'00"
109°57'30"
Figure 14A
38°25'00"
109°55'00"
0
1 km
Figure 7B

Fig. 6

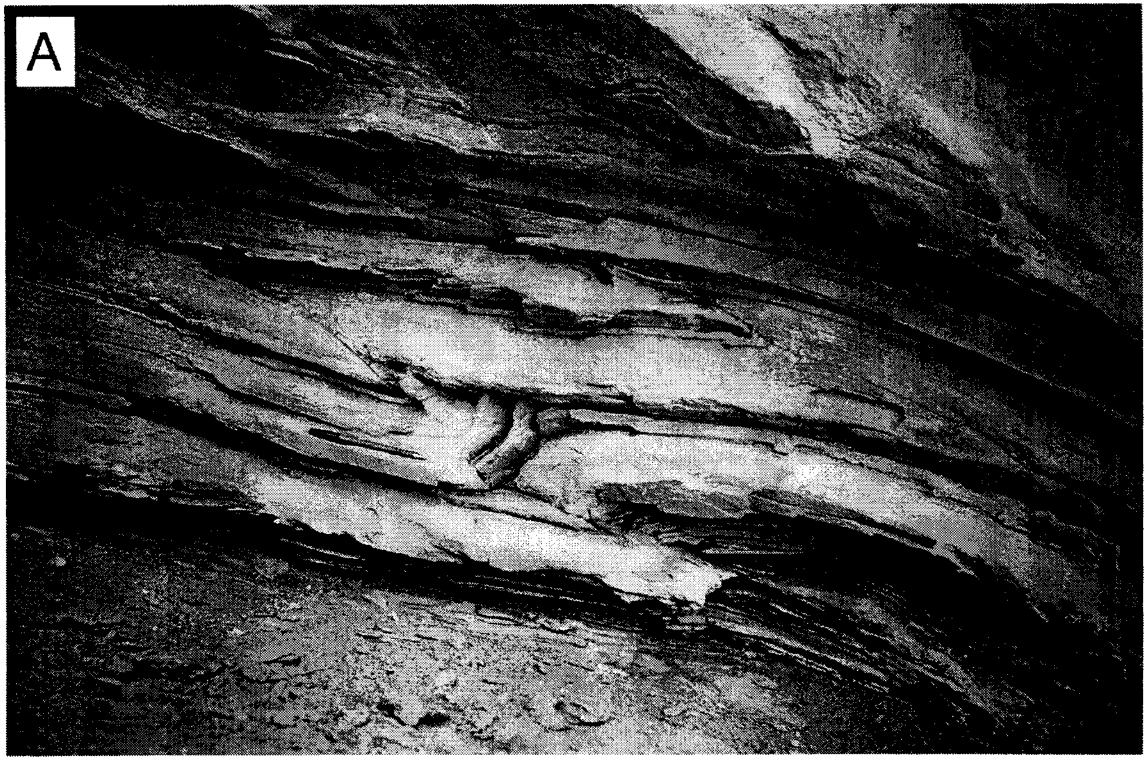


Fig. 7A

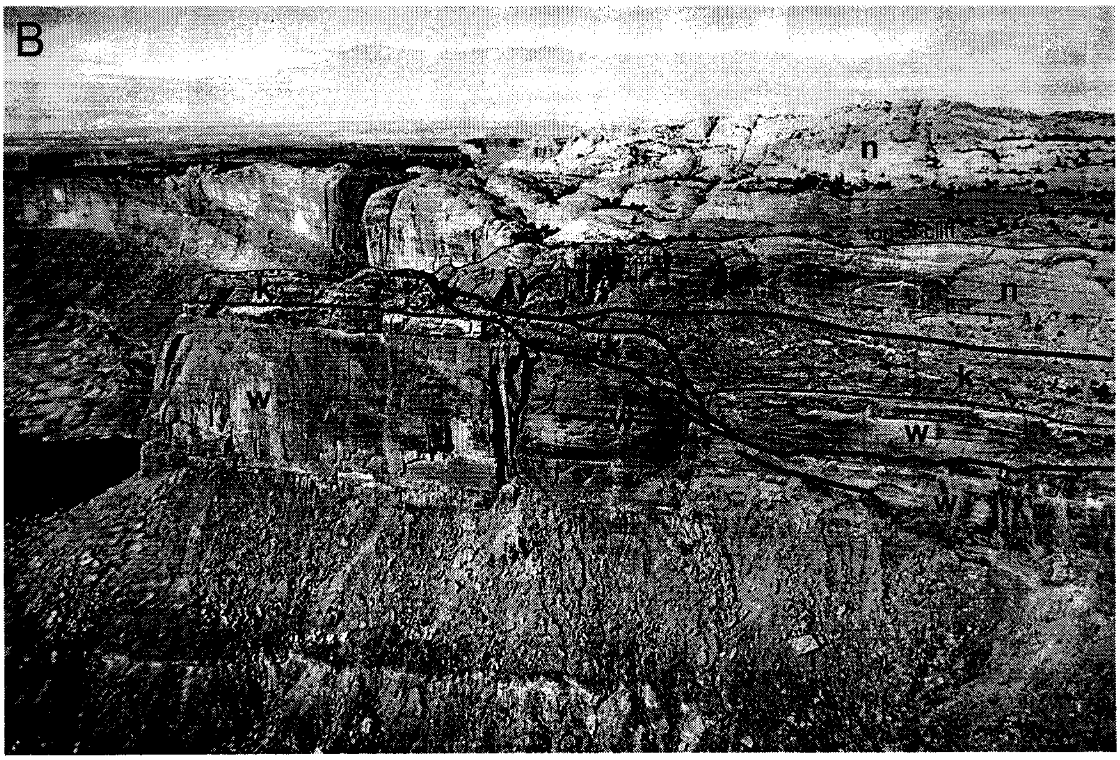
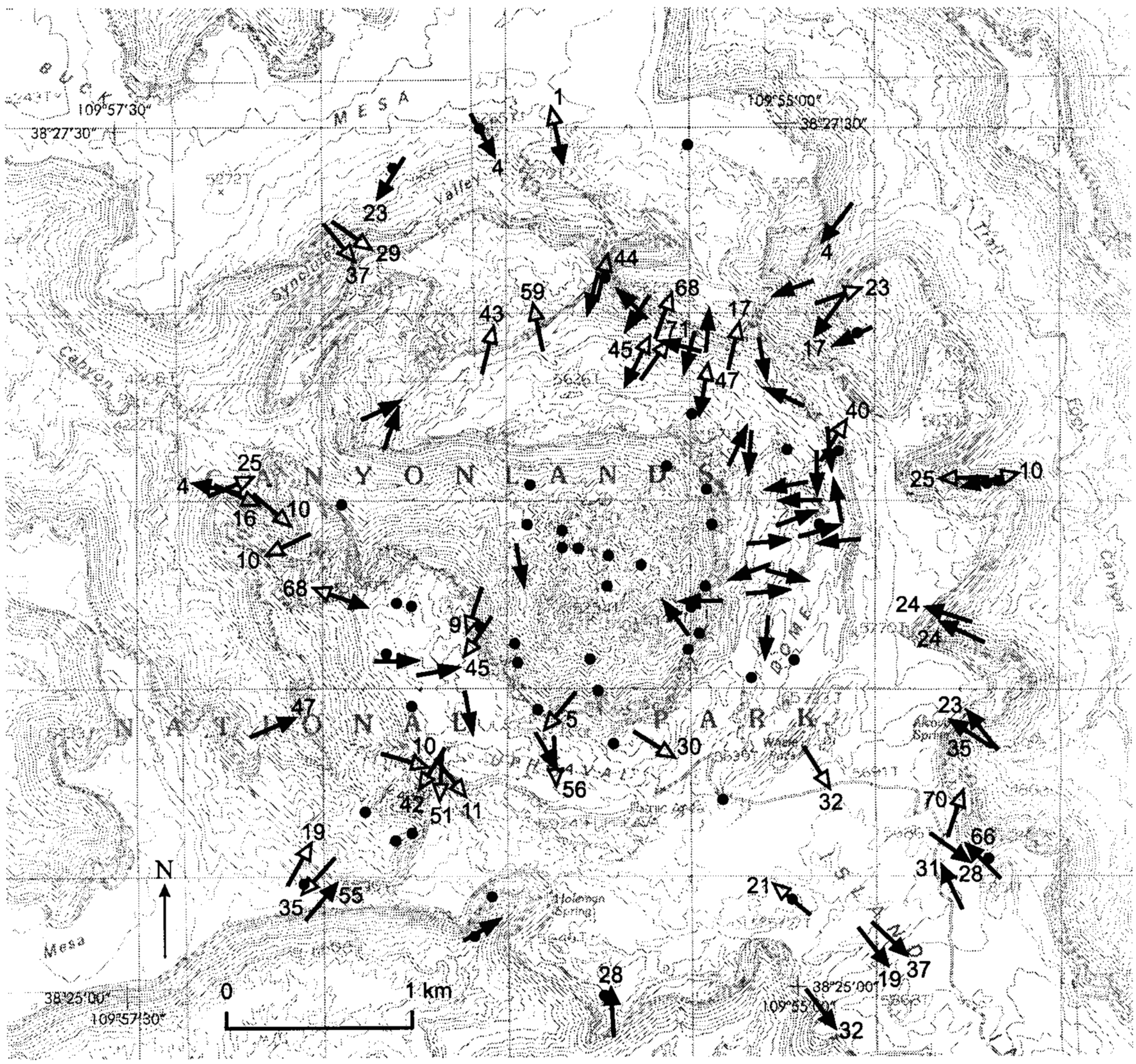


Fig. 7B

FIGURE 7c.



17 — trend and plunge of fault striae, relative motion of hanging wall uncertain

31 — trend and plunge of fault striae, relative motion of hanging wall is down plunge

45 — trend and plunge of fault striae (open arrow), relative motion of hanging wall is up plunge (filled arrow)

approximate direction of relative motion of hanging wall inferred from drag folds

clastic dike locality

Fig. 8

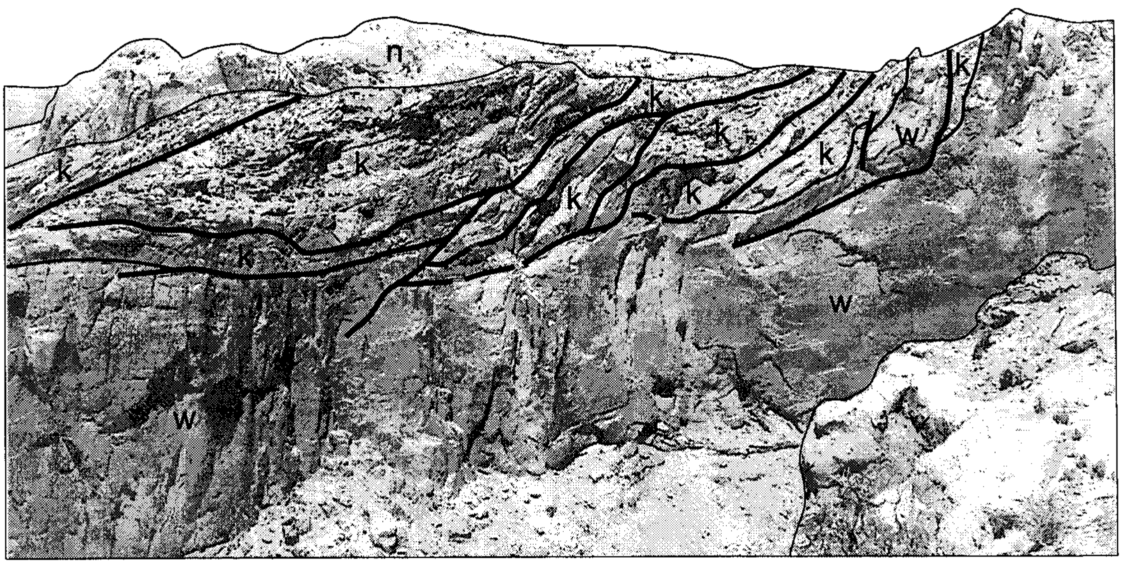
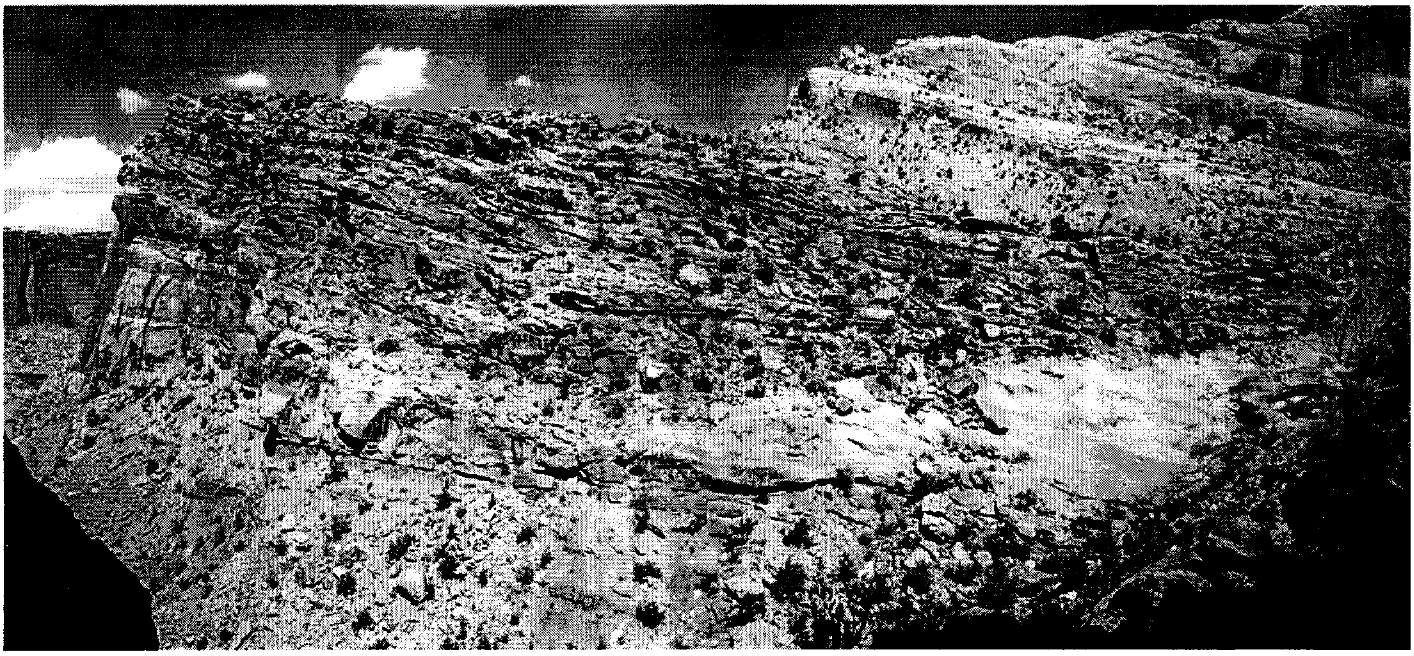


Fig. 9

Fig. 10



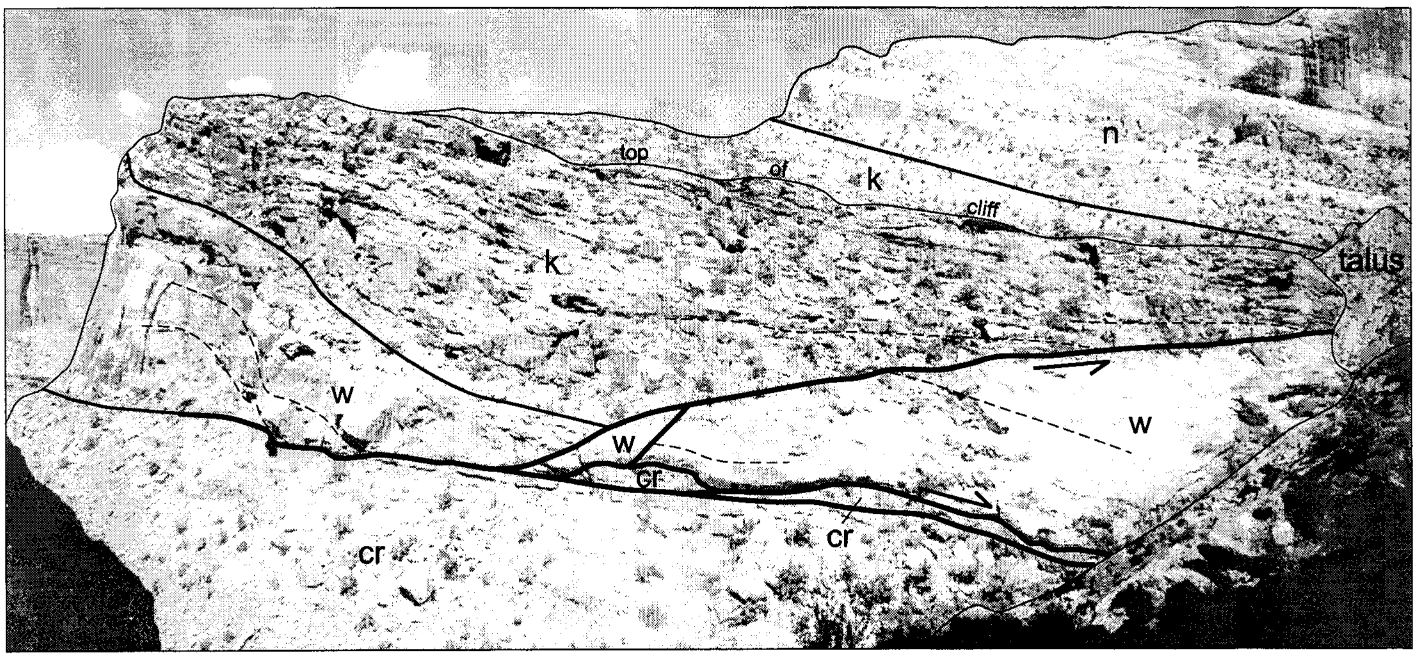


Fig. 11

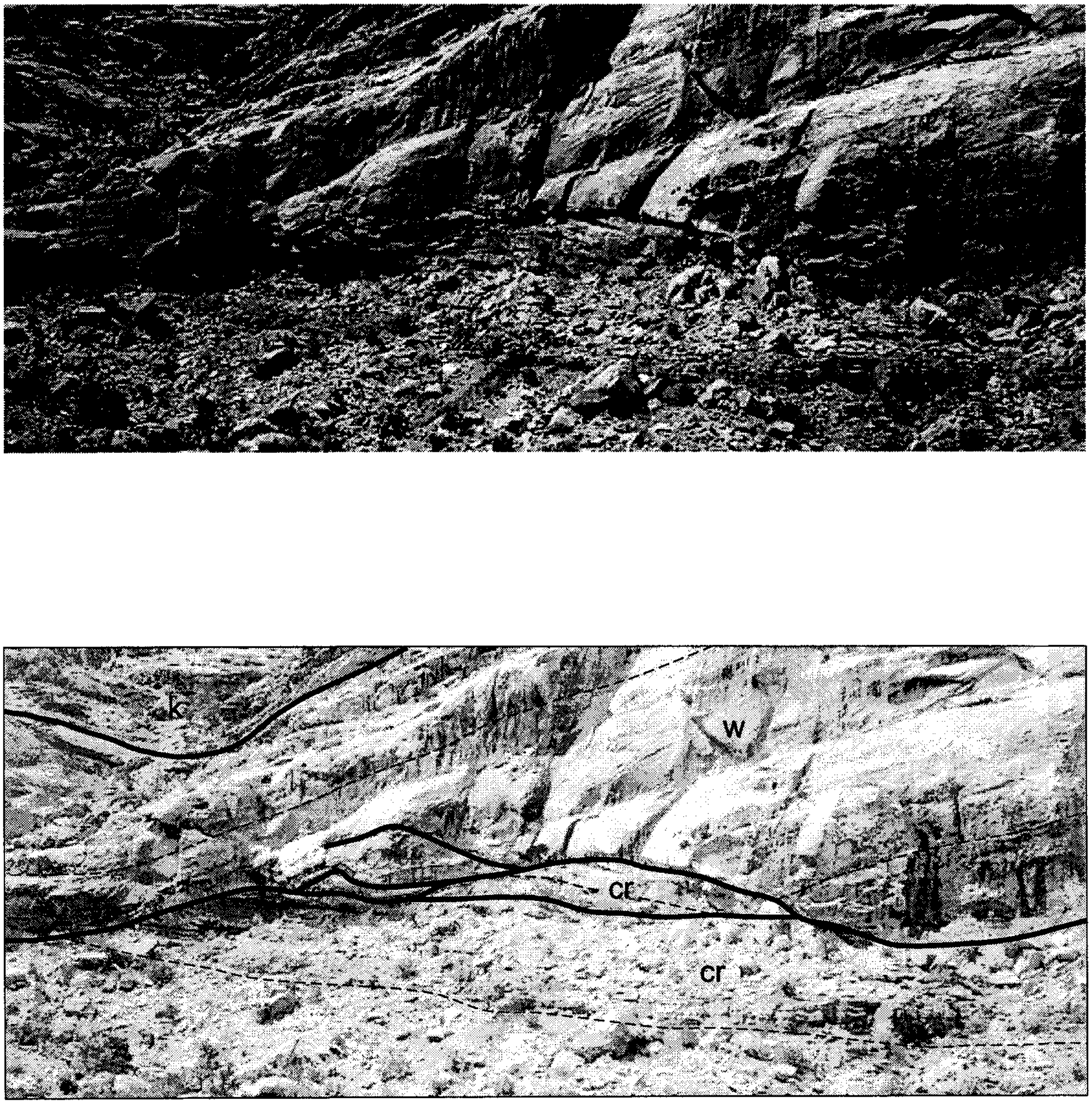


Fig. 12

Fig. 13

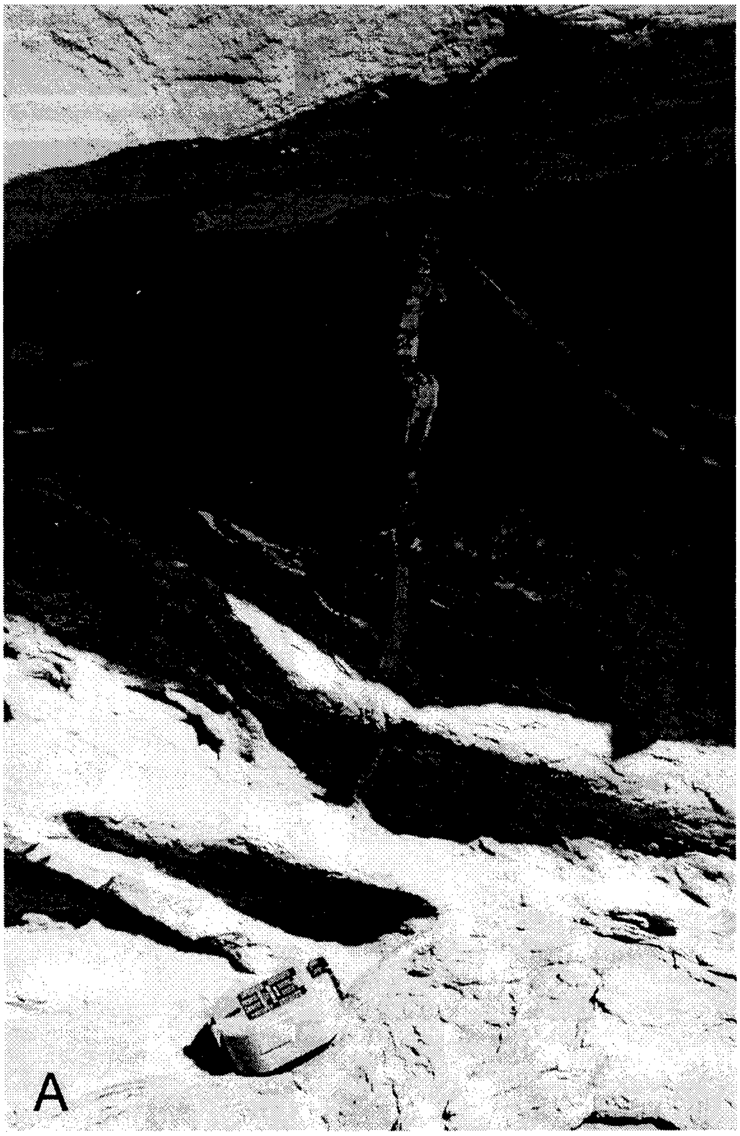


Fig. 14A

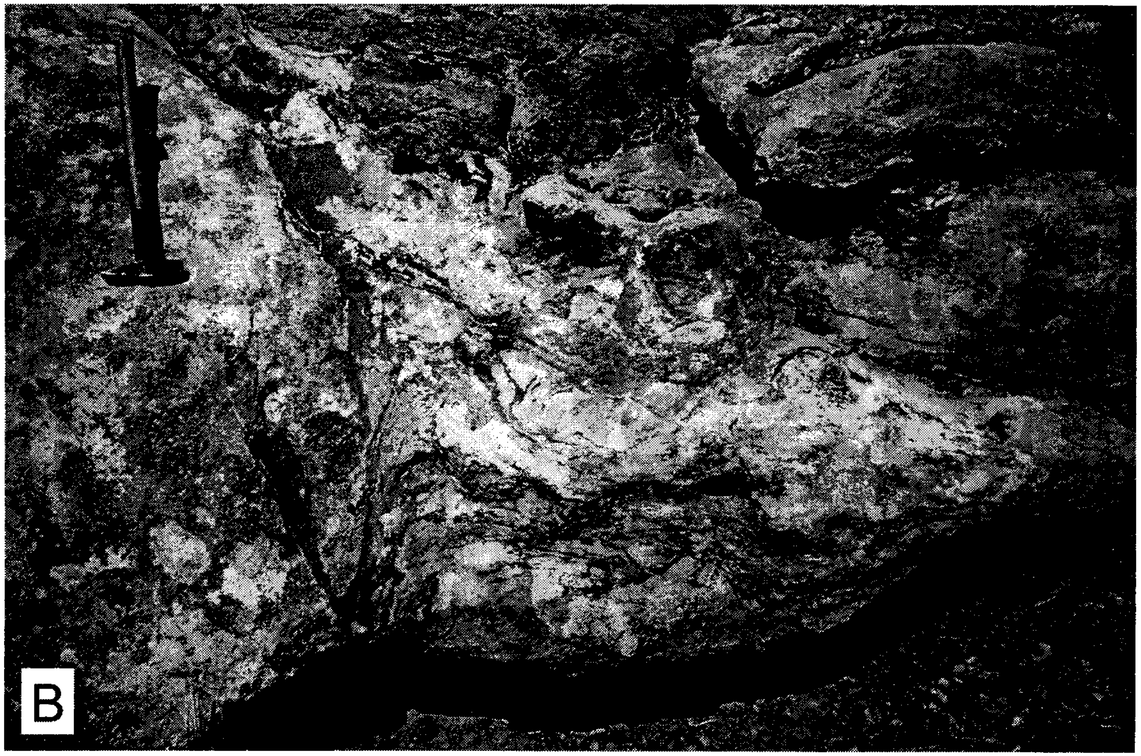
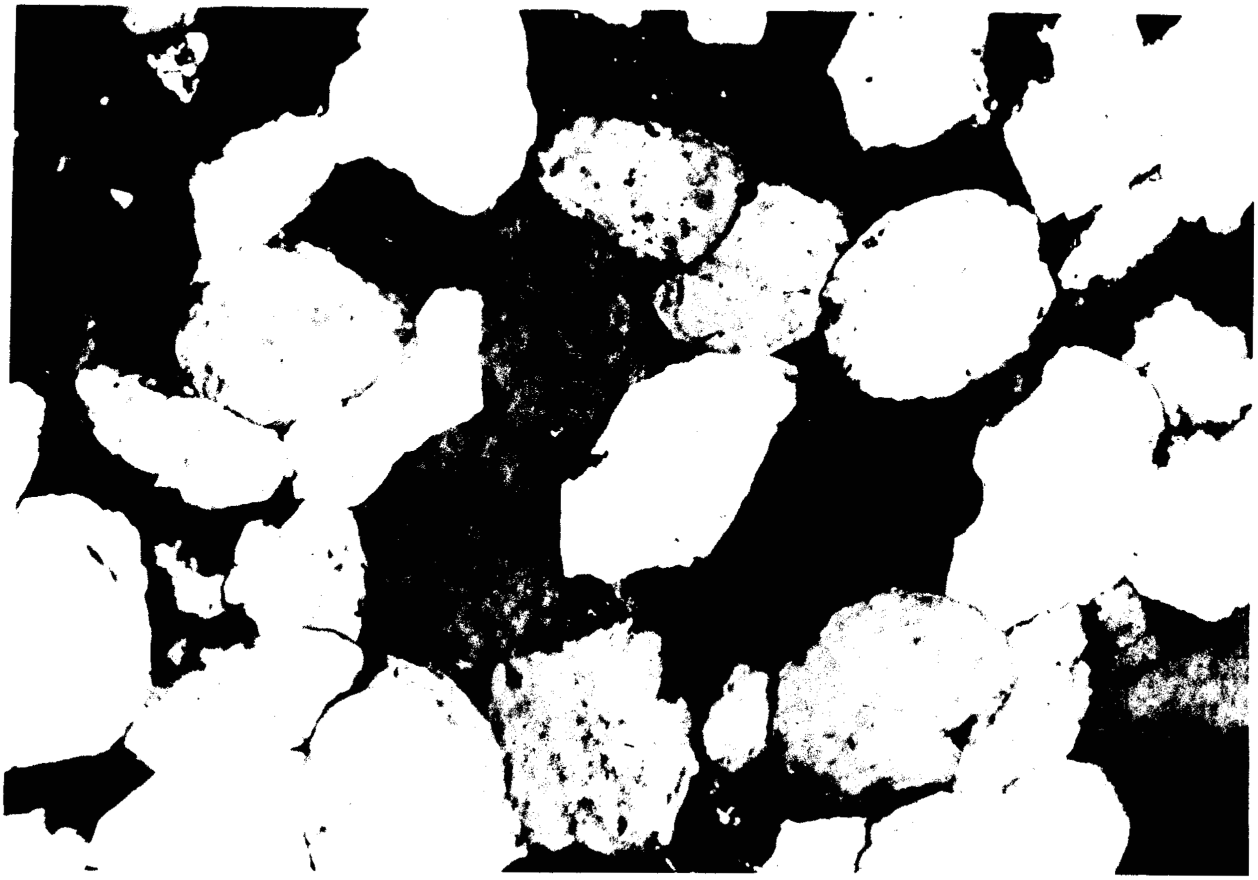
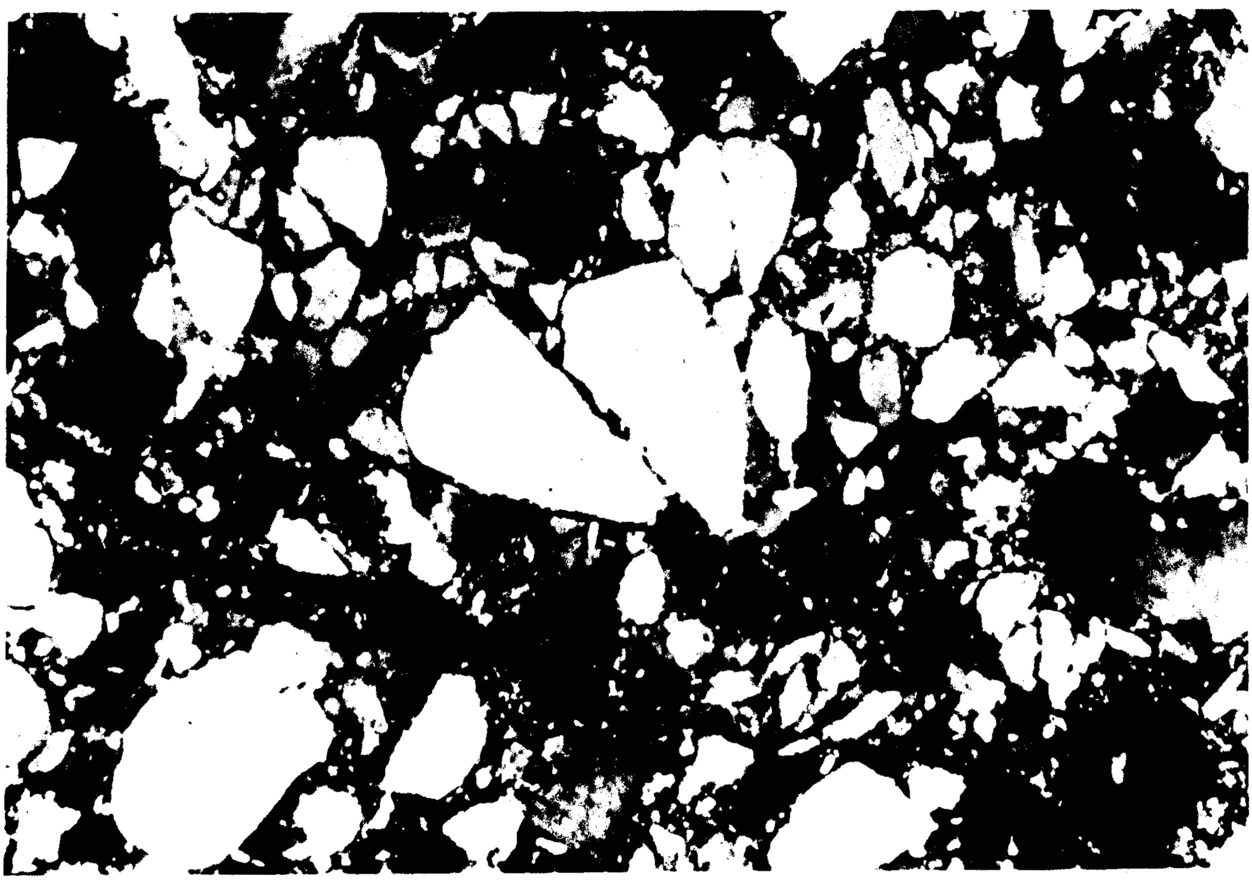


Fig. 14B



a.



b.

FIGURE 15.

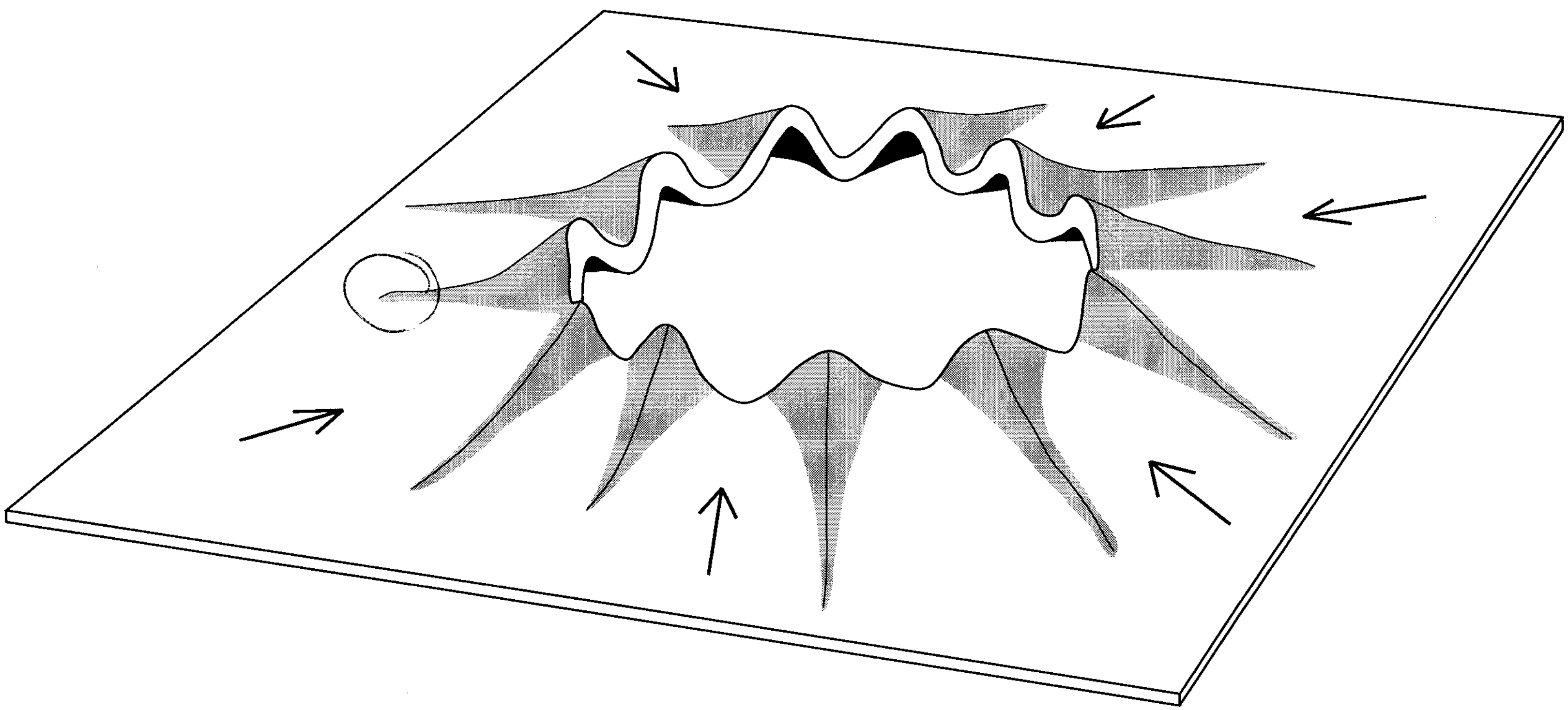


Fig. 16

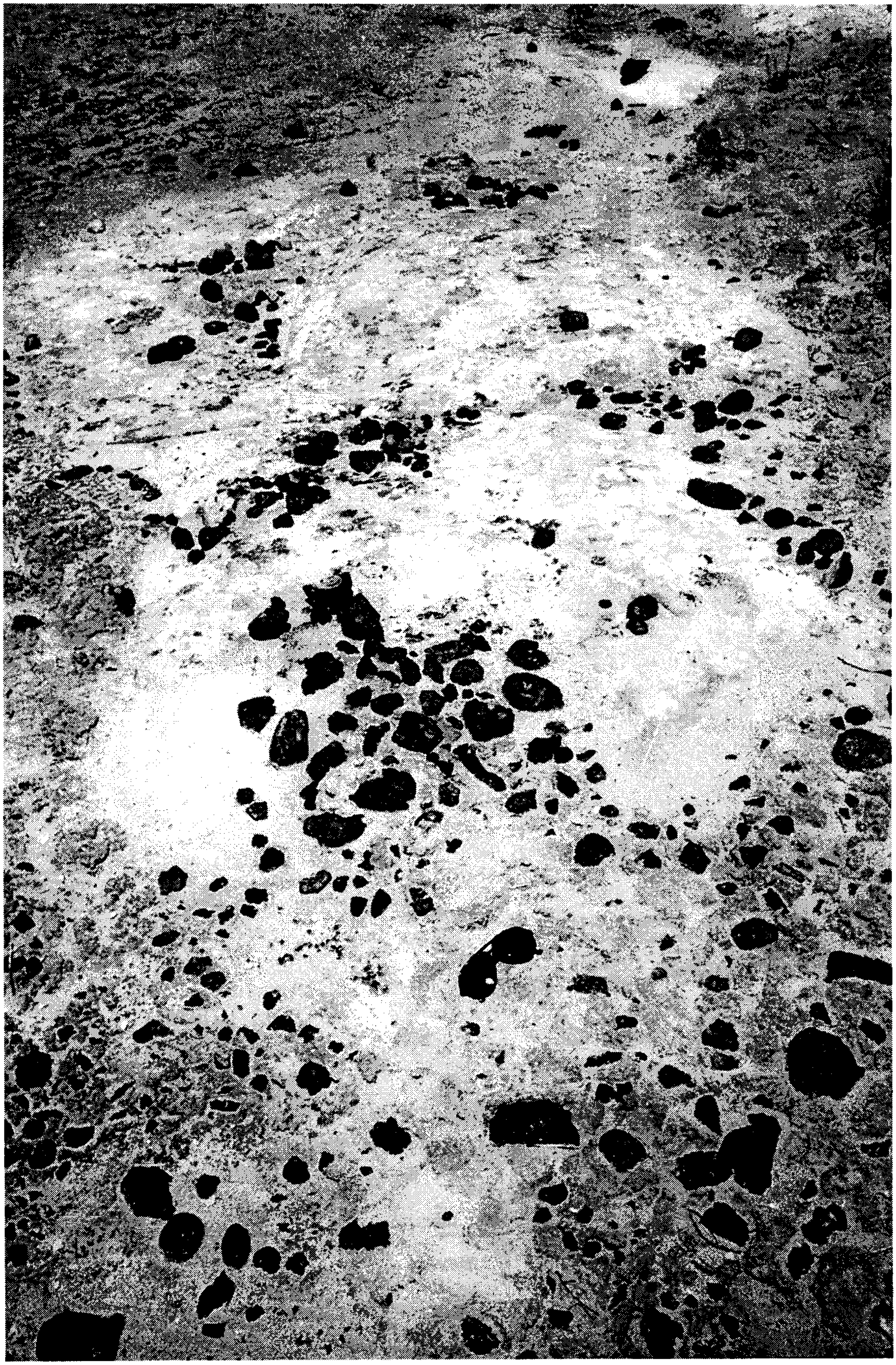


Fig. 17

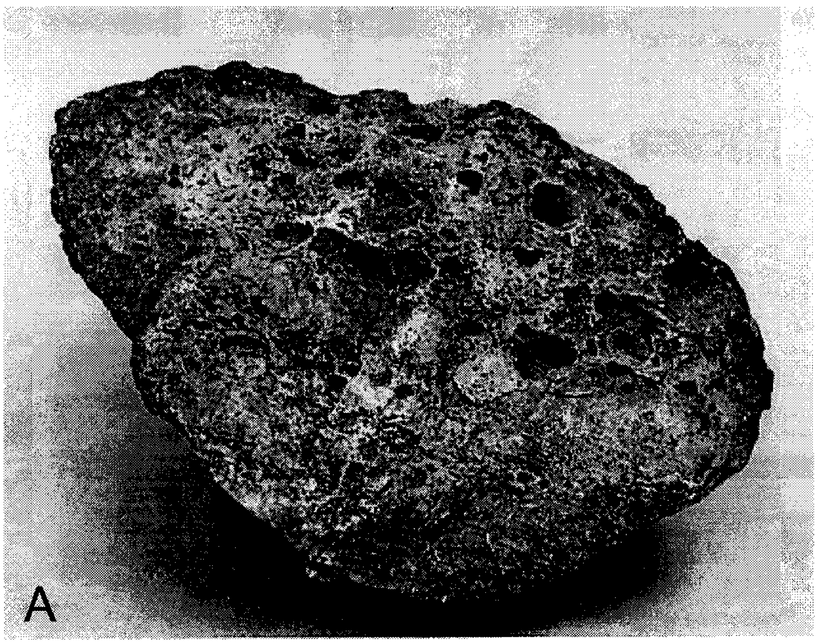


Fig. 18A

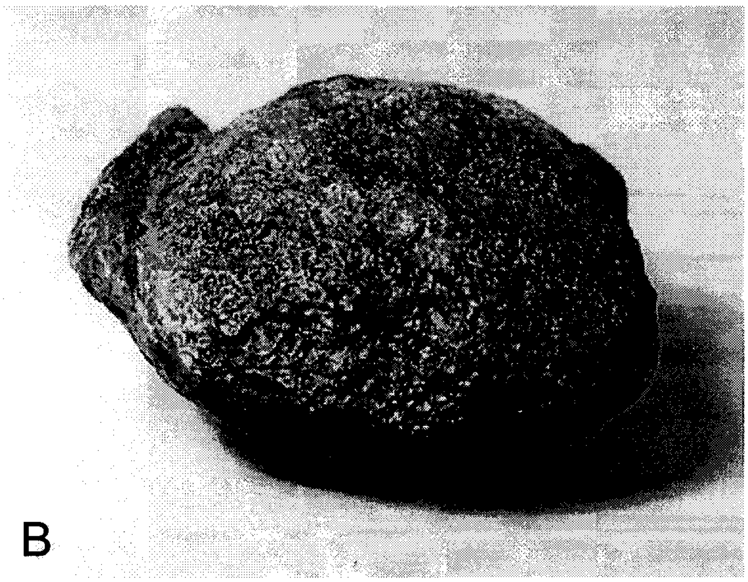


Fig. 18B

Fig. 18C

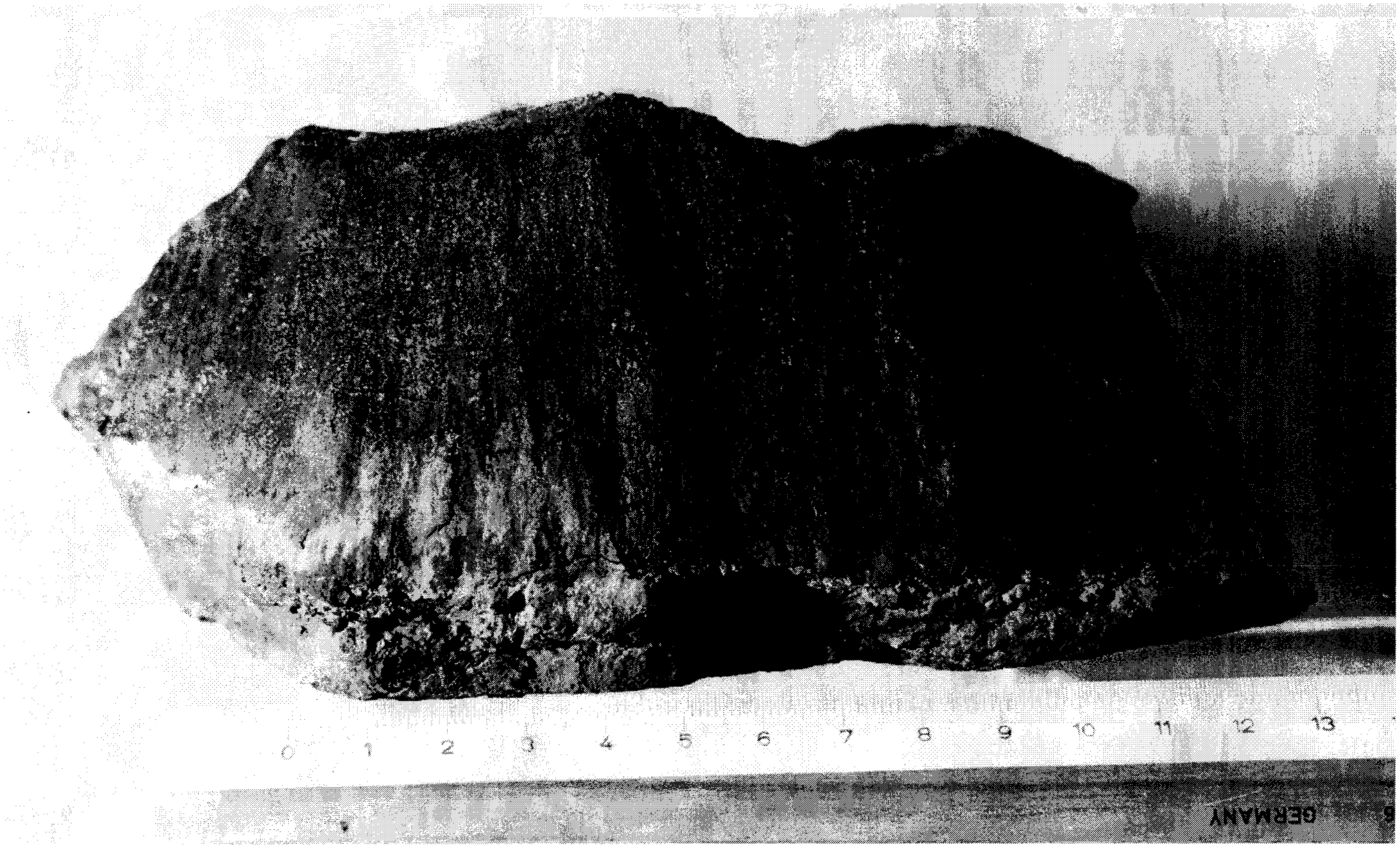


Fig. 19

LEGEND FOR UPHEAVAL DOME CROSS-SECTION

ROCK UNITS

JURASSIC	n	Navajo Sandstone	
	k	Kayenta Formation	
JURASSIC to TRIASSIC	w	Wingate Sandstone	
TRIASSIC	cr	Church Rock Member	Chinle Formation
	bl	Black Ledge Member	
	p	Petrified Forest Member	
	bc	basal conglomeratic sandstone	
	s	Sewemup Member	Moenkopi Formation
	ua	upper Ali Baba Member	
	la	lower Ali Baba Member	
	h	Hoskinnini Member	
PERMIAN	wr	White Rim Sandstone of the Cutler Group	
	c	Cutler Group underlying the White Rim Sandstone	
PENNSYLVANIAN	ht	Honaker Trail Formation	
	px	Paradox Formation	

SYMBOLS

.... — — ———	contact, depositional outside of regional monocline, possibly a fault zone in many places elsewhere, dashed where approximately located, dotted where inferred
. . . ▬ ▬ ▬▬▬	fault, dashed where approximately located, dotted where inferred
\ /	apparent dip of bedding

ROCK UNITS

Age	Symbol	Unit	Formation
JURASSIC	n	Navajo Sandstone	
	k	Kayenta Formation	
JURASSIC to TRIASSIC	w	Wingate Sandstone	
TRIASSIC	cr	Church Rock Member	Chinle Formation
	bl	Black Ledge Member	
	p	Petrified Forest Member	
	bc	basal conglomeratic sandstone	
	s	Sewemup Member	Moenkopi Formation
	ua	upper Ali Baba Member	
	la	lower Ali Baba Member	
	h	Hoskinnini Member	
PERMIAN	wr	White Rim Sandstone of the Cutler Group	

SYMBOLS

contact, depositional outside of regional monocline, possibly a fault zone in many places elsewhere, dashed where approximately located (within 40 feet), dotted where concealed or inaccessible

fault, normal displacement shown with bar and ball on downthrown side, reverse displacement shown with teeth on hanging wall, dashed where approximately located (within 40 feet), dotted where concealed or inaccessible

64 strike and dip of bedding

horizontal bedding

strike and dip of vertical bedding

76 strike and dip of overturned bedding

22 strike and dip of fault

strike and dip of vertical fault

5 axial trace and approximate plunge of fold, showing downplunge view of fold shape

31 trend and plunge of fold axes, showing downplunge view of fold shape

axial trace of regional syncline

axial trace of regional monocline